

DISCUSSION DRAFT

DECEMBER 10, 2013

Biobased and Degradable Plastics in California

**Understanding New Packaging Materials
and Their Management**

California Department of Resources Recycling and Recovery (CalRecycle)

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Executive Summary

(Will be published in Final Draft)

Introduction

Recyclers and composters increasingly are discussing bioplastics, as more companies adopt this broad class of materials for products and packaging. Though a small segment of all plastics today, bioplastics seem poised to expand significantly, with important implications for their end-of-life (EOL) disposition. More broadly, their emergence offers insight into a changing materials marketplace just as California moves to implement ambitious new recovery goals.

This report discusses the results of bioplastics-related research funded by the California Department of Resources Recovery and Recycling (CalRecycle) over the past several years. The Introduction provides background information to put these research projects in context, with particular attention to packaging and an eye toward clearing up confusion surrounding bioplastics.

Part I explores the science and economics of producing bioplastics. It discusses the range of materials under the “bioplastic” umbrella and ways in which they are made, research at Stanford University into methane-based bioplastics, economic considerations for producing such resins in California, and the role of these new materials in the Green Chemistry movement and in public health issues relating to plastics generally.

Part II addresses the implications of bioplastics for California’s recycling and composting infrastructure. The section covers the collection, sorting, and processing of materials; the role of contamination in recovery systems; the potential of improved technology for both reducing contamination and capturing additional packaging and products at the end of their lives; and selected environmental implications of manufacturing with bioplastics.

Part III presents lessons learned from the CalRecycle-funded research described in this report, a brief analysis of the implications these research findings may have for our state, and some thoughts on where the introduction of new materials and technologies could lead in the future.

Packaging in California

Packaging is like the chatter in a crowded café: we notice it at first, but pretty soon we barely give it a second thought. We open a package, remove the contents, and off it goes to the recycle bin or – all too often – to the trash. And then it’s just... gone. Even avid recyclers may not know what happens “beyond the bin.”

Yet packaging brings into focus the crucial role of natural resources in modern life. The raw materials used to make packaging have to come from somewhere, of course. Traditionally “somewhere” was a mine, a tree, a barrel of oil extracted from the depths of the earth. What happens to packaging at the end of its useful service is equally critical. We have come to realize the recovery of used packaging materials, or any used materials, is central to sustaining our environment and our economy. Packaging discarded is a resource wasted.

Note the essential function of packaging actually is to conserve resources: without it we would see more spoiled food, more damaged goods to be replaced, more raw materials and energy gone to waste. A product’s package also may provide useful consumer information (think nutrition labels), not to mention its utility as a marketing tool. But unfortunately these up-front attributes may have little connection to disposition of packaging materials at the back end. Packaging can be excessive, or poorly designed so it cannot be recycled, or constructed with layers that cannot

be separated economically, or made in a way that interferes with recovery systems, or made from ingredients that release toxic chemicals... the list goes on. Packaging, in fact, has a “life” of its own, one that may continue long after we think we are done with it.

As the number of products in the California marketplace has mushroomed, so too has the variety and complexity of packaging. Naturally brand owners want to differentiate their products from their competitors, and so we see an influx of new shapes, sizes, and forms. New materials and physical properties enhance shelf life or improve supply chain efficiency. While the rapidly changing packaging landscape may offer consumers greater choice and convenience, it also challenges the State’s recycling and composting systems – and potentially burdens our air, land and water.

This wave of new packaging comes at a time of heightened environmental awareness. In California this has given rise to several key policy efforts:

- Mounting evidence of human contributions to climate change resulted in the landmark Assembly Bill 32, the Global Warming Solutions Act of 2006 (Nuñez, Chapter 488, Statutes of 2006). That law calls for a reduction in greenhouse gases (GHGs) to 1990 levels by 2020. The California Air Resources Board (CARB) recently implemented a ground-breaking cap-and-trade program to begin the journey toward this goal. The CARB is preparing a 2014 update of the Scoping Plan.
- Concern over the dramatic rise in chemical use in recent decades prompted the California Green Chemistry Initiative, including legislation in Assembly Bill 1879 (Feuer, Chapter 599, Statutes of 2008). In that effort, the California Department of Toxic Substances Control (DTSC) is pursuing a new approach to protecting human health and the environment, encouraging manufacturers to design safer products at the outset rather than manage hazardous wastes once products are discarded.
- Worry over rising pollution off our coast led to Senate Bill 1319, the California Ocean Protection Act (Burton, Chapter 719, Statutes of 2004). The law created the Ocean Protection Council (OPC), a collaborative attempt to identify and reduce the many pressures on the health of our marine resources. The OPC’s 2007 resolution to reduce marine debris¹, in fact, was one impetus behind several of the projects detailed in this report.
- Renewed efforts to manage and recover more materials, as embodied in Assembly Bill 341 (Chesbro, Chapter 476, Statutes of 2011), discussed below.

The Role of California’s Recovery Infrastructure

CalRecycle has been coordinating closely with the lead agencies and stakeholders to support the policy efforts above. Source reduction, recycling and composting offer benefits in each of these areas. Recycling can dramatically reduce energy use over a product’s life cycle, for instance, which in turn lowers production of GHGs. California’s beverage container recycling program, which places a refund value on bottles and cans to encourage their return, keeps land-based litter out of the ocean. (Up to 80 percent of marine litter originates on land.²) CalRecycle’s used oil and electronic waste programs, among others, help keep toxic materials out of our land and water.

In 2012, CalRecycle embarked on an ambitious new effort as a result of AB 341 to move California beyond our current recovery achievements. AB 341 directed the Department to provide

strategies to source reduce, recycle or compost at least 75 percent of the State's solid waste by 2020. This 75 percent recycling goal is an aspirational leap beyond the mandates of AB 939 (Sher, Chapter 1095, Statutes of 1989), which established the existing 50 percent diversion requirement for local jurisdictions. The State now diverts the equivalent of 65% of its municipal solid waste from landfills, but this includes some material sent to transformation facilities and some material used as alternative daily cover or for other applications at landfills. In 2014 CalRecycle will report to the Legislature on strategies to accomplish this goal. Clearly some programs must expand, new waste prevention and recovery efforts must begin, and the concerted efforts of diverse stakeholders and the general public will be required to meet this challenge.

The sheer volume of additional materials that needs to be collected in the coming years to meet this 75 percent goal will tax our existing system of recovery programs and physical infrastructure. Cross-contamination of recycling streams adds to the burden. Successful recycling typically requires separation and cleaning of materials before they are shipped to manufacturers to make new products, but the introduction of incompatible materials makes it difficult to accomplish this and leads to processing "yield loss" that ends up in disposal.

Plastic packaging, for instance, usually must be sorted into one of seven or more resin types before processing the material into industrial feedstock acceptable to manufacturers. Thus, material or functional innovations that increase sales or consumer convenience but which mix resins or have other features may have the unintended consequence of creating havoc with recovery equipment that was not designed to process such items. Moreover, these effects add to recovery costs. The recent trend in full-wrap labels on beverage bottles is an example, as the labels can impede the "sink-float" method of separation used by most plastic reclaimers.*

Examining Bioplastics

Some in the environmental community and others hope a new class of materials, bioplastic goods and packaging, could lead us to a more sustainable means of production. Whether biodegradable or sourced from renewable materials, or both,[†] these polymers have rapidly gained market share, though they still comprise a small part of all plastics produced. The sales growth reflects manufacturers' efforts to mitigate a host of environmental concerns, including air and water pollution, ever more precarious supplies of oil, and chemicals in commerce that may affect human health in ways we are only beginning to understand.

Indeed, marketing claims for bioplastics have touted those very qualities. Bioplastics, manufacturers say, create fewer GHGs than the materials they replace. Or they assert packages made from these new resins will biodegrade after use, absorbed naturally into the earth or seas. Or they claim bioplastics avoid the toxic effects of their fossil-based counterparts. Or perhaps the new plastics will free us from our addiction to oil. In short, advocates believe packaging produced from bioplastics is more sustainable than the status quo.

* See the Association of Post-Consumer Plastic Recyclers' website for a full discussion of this issue: <http://www.plasticsrecycling.org/technical-resources/sleeve-labels>.

[†] A glossary of key terms may be found at the end of this report.

Discerning the truth of such claims is not an easy task. The science surrounding claims of environmental sustainability – however we define “sustainability” – is evolving. The discipline of Life Cycle Assessment (LCA) attempts to analyze all material and energy inputs and outputs over the entire life of a product, from raw material acquisition through manufacturing and consumer use and finally to the material’s ultimate recovery or disposal. While an LCA can be a powerful tool for examining real-world environmental consequences and weeding out overzealous marketing claims, an LCA of any given packaging or product system is fraught with challenges, from setting appropriate study boundaries to incomplete data sets.

What is clear is that bioplastic packaging in the California marketplace has created significant consternation among recyclers and composters. Both groups are finding these plastics to be essentially incompatible with current practices and equipment. Bioplastics are seen by some as yet another hindrance to producing high quality, economical feedstock for the State’s manufacturers and agriculture.

Polyethylene terephthalate (PET) reclaimers, for instance, point to detrimental physical changes to the pellets they produce if degradable bioplastics are introduced into the reclaiming process. They worry that the very qualities that make some bio-resins desirable – like degradability – will be the undoing of their own product. Likewise, industrial composters find so-called “compostable” plastics may not degrade as claimed, and fear the release of unknown ingredients will compromise the quality of their end product.

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To provide more information on these issues, the Department sponsored several research projects at California universities to explore the science and economic implications of bioplastics used for packaging. These included a major effort at Stanford University to create a naturally occurring plastic by feeding a waste material, methane – a major component of biogas produced at landfills and wastewater treatment plants, and a potent greenhouse gas – to specialized bacteria. Researchers also examined the cost, life-cycle and recycling implications of this and other bioplastic materials.

Concurrently, the Department funded a study by the University of California at Berkeley of the statewide economic potential for producing the Stanford bioplastic; life-cycle studies of bioplastics and PET at the University of California at Davis, Santa Barbara and Berkeley; and biodegradation and toxicological assessments from California State University, Chico, and the Lawrence Berkeley National Laboratory. In addition, DTSC staff examined costs associated with a hypothetical biorefinery producing and recycling certain bioplastics, and the non-governmental organization Future 500 pilot-tested a mobile system for sorting bioplastic packaging from other types. *Table 1* lists the CalRecycle-funded studies.

Table 1 – Studies related to bioplastics and other resins funded by CalRecycle

Title	Principal Investigator(s)	Description
<i>Renewable Bioplastics and Biocomposites From Biogas Methane and Waste-Derived Feedstock: Development of Enabling Technology, Life Cycle Assessment, and</i>	Craig S. Criddle Stanford University	Laboratory research investigating the potential of developing a biodegradable PHB polymer using waste methane produced by landfills, wastewater treatment plants or anaerobic digestion facilities.

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<i>Analysis of Costs</i>		
"Economic Analysis of PHB Production" (Chapter 12 in the study above, referred to in this report as the Stanford PHB cost study)	Craig S. Criddle, Weimin Wu Stanford University	Using data from the Stanford laboratory team, an LCA on the process conducted by Stanford researchers (see below) and other sources in the literature, the authors estimated the costs associated with producing the Stanford PHB at commercial scale.
<i>Bioplastics in California - Economic Assessment of Market Conditions for PHA/PHB Bioplastics Produced from Waste Methane</i>	David Roland-Holst University of California, Berkeley	Modeled the economic potential for building and operating a small-output PHB plant at certain locations in California using the Stanford process, based on local methane availability and recovery at landfills and wastewater treatment plants.
<i>Cradle-to-Cradle Economic and Environmental Assessment of a California Biopolymer Industry Using Material Recovery Facility Residuals</i>	Alissa Kendall, Nathan Parker University of California, Davis	Modeled a large, centralized facility that would create PHA resins using residual organic waste from material recovery facilities and produce millions of pounds of resin per year. Examined the life-cycle environmental impacts of a hypothetical plant as well as optimal economic considerations.
<i>Experimental Comparison of Chemical Migration from Petrochemical Plastic and Bioplastic Bottles into Drinking Water</i>	Randy Maddalena Lawrence Berkeley National Laboratory	Identified the ingredients (additives and chemicals) found in plastic water bottles made from petrochemical plastics and bioplastics, and analyzed the extent to which such chemicals might leach into water contained in them.
<i>Life Cycle Assessment of polyethylene terephthalate (PET) Beverage Bottles Consumed in the State of California</i>	Roland Geyer, Brandon Kuczenski University of California, Santa Barbara	Conducted an LCA to characterize the resource requirements and environmental impacts associated with the use of polyethylene terephthalate (PET) to manufacture beverage bottles delivered to the California market.
<i>Cradle-to-Gate Life Cycle Assessment for a Cradle-to-Cradle Cycle: Biogas-to-Bioplastic (and Back)*</i>	Katherine Rostkowski Stanford University	Analyzed the environmental life cycle of producing the Stanford PHB to the point of producing resin pellets as feedstock for manufacturers.
<i>PLA and PHA Biodegradation in the Marine Environment</i>	Joseph Greene California State University, Chico	Analyzed the fate and persistence of PLA and PHA bioplastics during biodegradation in the marine environment, using standardized laboratory testing.
<i>PHA Biodegradable Bottle Development and Testing</i>	Joseph Greene California State University, Chico	Studied the potential production of PHA-based bioplastic bottles to identify co-polymers that could be suitable for plastic bottle manufacturing.
<i>The Bioplastics Sorting Project</i>	Future 500	Developed a mobile optical sorting system to test separation of bioplastics from several waste streams at material recovery facilities (MRFs) and reclaiming facilities. Project included stakeholder input and an analysis of discarded plastics lost to landfills in the state.
<i>Summary and Synthesis for California's Bioplastics Life Cycle Assessment Projects</i>	Arpad Horvath, Mikhail Chester	Peer review of other CalRecycle-related plastic LCA

* The Stanford LCA was not funded by CalRecycle, but was closely associated with the Stanford laboratory research. Its findings are summarized in Part II.

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	University of California, Berkeley	projects for consistency with scientific best practices.
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To put the studies detailed in this report in context, *Figure 1* depicts them in relation to stages of bioplastic production and recovery. (Those studies that have been published may be downloaded at <http://www.calrecycle.ca.gov/Publications/Default.aspx>.)

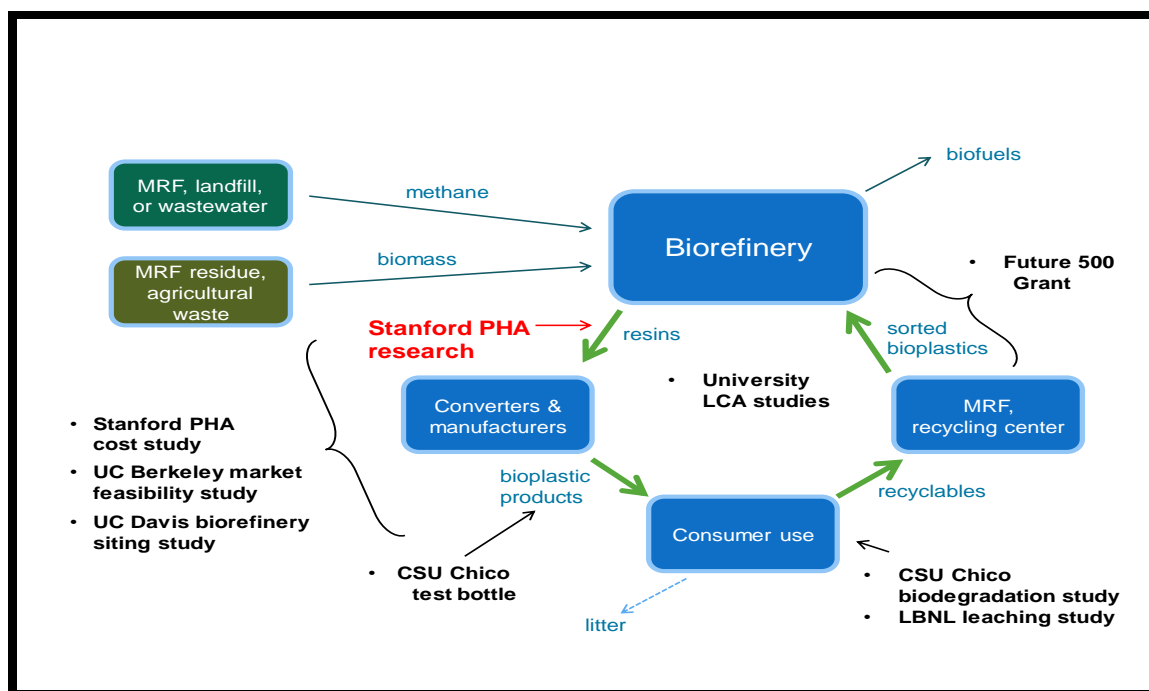


Figure 1 – Bioplastics-related research funded by CalRecycle

CalRecycle’s goal in these efforts was to offer an impartial examination of the scientific data and economic realities underpinning the introduction of new bioplastic packaging materials in the State. Our objectives included

- educating the public and clarifying misconceptions about bioplastics;
- encouraging dialog among stakeholders both in favor and skeptical of these new materials;
- identifying data gaps and areas for future research;
- identifying current and future infrastructure needs for the recycling and composting industries; and
- evaluating packaging with a life-cycle lens, rather than the traditional “end-of-pipe” approach to regulation.

The research discussed here does not constitute a complete environmental assessment of bioplastics vis-à-vis their fossil-based analogues. But as markets and materials evolve, so too

must our understanding of the issues surrounding change. This report is meant to provide objective evidence to help California consider the context of bioplastics in our recovery programs as these new materials inevitably enter the marketplace.

PART I – The Science and Economics of Producing Bioplastics

What Are Bioplastics?

First, what are we talking about when we say “bioplastics”? Unfortunately, the term has been used to include a wide array of materials, some similar to each other, some different, and overall confusing to the consumer. But in general there are two broad categories of bioplastic materials, which we will use in our working definition for this report:

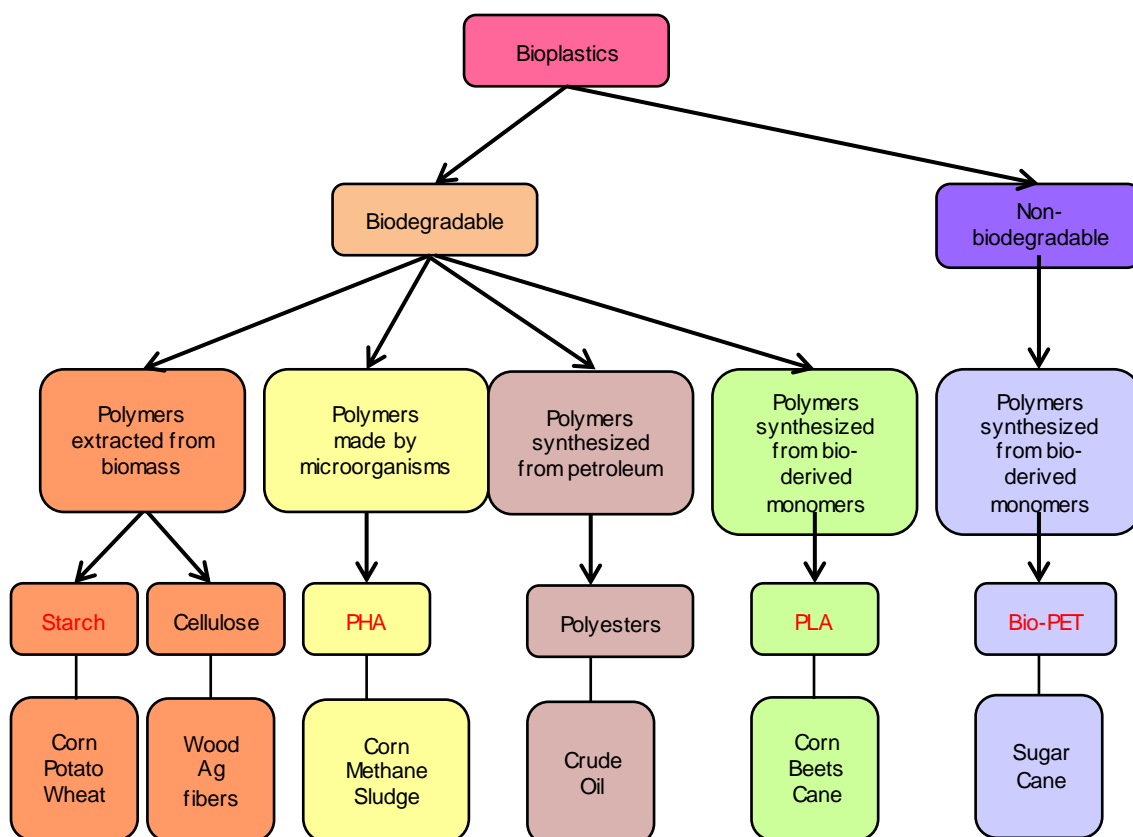
Bioplastic means a plastic made from *biobased*, renewable materials OR a plastic that is *biodegradable*.[§]

Note these two categories may overlap: a plastic can be made from corn, for instance, and biodegrade in the environment (more on biodegradation below). However, some biobased plastics do not biodegrade, and some petroleum-based plastics are biodegradable.

Figure 2 depicts the generally understood universe of bioplastics used in packaging and typical feedstock sources. These are created through a variety of processes, both synthetic and naturally occurring, typically in facilities known as “biorefineries.”^{**} The list is not exhaustive but gives a snapshot of the main categories used in packaging.

[§] The International Union of Pure and Applied Chemistry (IUPAC) has attempted to standardize plastics nomenclature across industries. The organization discourages use of the term “bioplastic,” instead preferring “biobased polymer” to distinguish that class from fossil-derived resins. However, other groups continue to use “bioplastic” to describe a wide range of materials, so we will use a broader interpretation.

^{**} The term “biorefinery” is used in a variety of contexts. The National Renewable Energy Laboratory defines it as “a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass.” (<http://www.nrel.gov/biomass/biorefinery.html>) In general, the term refers to a manufacturing plant that is analogous in some way to a traditional petroleum refinery, but one that uses biobased feedstocks. A biorefinery may produce a range of outputs, including “building-block” chemicals as well as bioplastic resins suitable for consumer products.



Source: Adapted from Platt, 2010³

PHA = polyhydroxyalkanoates. PLA = polylactic acid or polylactide. PET = polyethylene terephthalate.

The bottom row indicates typical feedstock sources for each group.

Figure 2 – Major categories of bioplastics

This definition of bioplastics, while not universally adopted, casts the widest net to frame our discussion of bioplastic packaging. But when we ask, “How does bioplastic packaging affect the environment?” or “What impact do bioplastics have on recycling systems?” more details are required. Information about ingredients, temperature, physical environment (land, water, air), recovery method and even consumer use come into play.

A few related definitions and processes are critical to understanding the technical and policy questions surrounding bioplastics. Below are some key concepts to put bioplastics in context.

Biobased – This term generally connotes a material produced from renewable sources rather than fossil-based feedstock. The U.S. Department of Agriculture BioPreferred Program defines a biobased product as “a commercial or industrial product... composed, in whole or in significant part, of biological products, including renewable domestic agricultural materials (including plant, animal and aquatic materials), forestry materials or intermediate materials or feedstock.”⁴

The American Society for Testing and Materials (ASTM, now ASTM International) more precisely calibrates the term to mean the amount of “new” or biogenic carbon (e.g., not fossil-based) contained in a product or material. The test method for determining this, ASTM D6866,

defines biobased content as “the amount of biobased carbon in the material or product as a percent of the weight (mass) of the total organic carbon in the product.”^{5††}

In this report, “biobased” resins include naturally occurring plastics created in bacterial cells using waste methane and other feedstocks (the polyhydroxyalkanoate or PHA family of bioplastics). Synthetic plastics like polylactic acid (PLA) derived from corn also are biobased.

Degradable Plastic – ASTM broadly defines degradable plastics as those that are “designed to undergo a significant change in [their] chemical structure under specific environmental conditions resulting in a loss of some properties...” But within this broad framework, ASTM defines explicit subcategories, including *biodegradable*, *hydrolytically degradable*, *oxidatively degradable* and *photodegradable* plastics.⁶ The organization provides detailed scientific standards and test methods related to many of these terms.

Of these terms, probably the one most likely recognized – and misunderstood – by the average consumer is *biodegradable*. Many people assume a product labeled with the word will simply break down quickly into soil, like leaves or grass. But scientists define the term more carefully. A biodegradable plastic according to ASTM is a degradable plastic “in which the degradation results from the action of naturally-occurring micro-organisms such as bacteria, fungi, and algae.”⁷

The Biodegradable Products Institute describes biodegradation this way:

“Biodegradation is a process that can take place in many environments including soils, compost sites, water treatment facilities, in marine environments and even in the human body. This is the process that converts carbon into energy and maintains life... In order for plastics to “biodegrade” they go through a 2 step process. First the long polymer chains are shortened or “cut”... by heat, moisture, microbial enzymes, or other environmental conditions... This first step IS NOT a sign of biodegradation!... The second step takes place when the shorter carbon chains pass through the cell walls of the microbes and are used as an energy source. This is biodegradation – when the carbon chains are used as a food source and are converted into water, biomass, carbon dioxide or methane (depending upon the process, takes place under aerobic or anaerobic conditions)... If you think of a long string of popcorn on a thread as a “plastic polymer” chain, then step one (fragmentation) is when the thread is cut randomly between the popcorn kernels... [In] the second step you [can] eat the popcorn and use it as a food.”⁸

A critical point: a plastic that merely fragments into small pieces, even if microscopic, does not truly biodegrade.

This, finally, brings us to the term *compostable*, often used to describe bioplastic bags and food serviceware. ASTM defines compostable plastic as “a plastic that undergoes biological

^{††} ASTM develops voluntary test methods (protocols for testing physical and chemical properties) and standard specifications (specific thresholds or conditions that must be met) for products in hundreds of industries through a consensus process. However, the methods and standards may become mandatory if adopted in statute or regulation. Most states, for instance, require certain plastic products and packaging to be labeled with Resin Identification Codes that are now administered by ASTM.

degradation during composting to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials and leaves no visually distinguishable or toxic residues.”⁹ ASTM Standard Specification D6400-12 prescribes three main requirements necessary for a plastic to be considered compostable in industrial facilities:^{##}

- *Disintegration* – No more than ten percent of the original dry weight of a product must remain after twelve weeks in a controlled composting test.
- *Biodegradation* – Ninety percent of the organic carbon in the whole item or for each organic constituent must be converted to carbon dioxide within 180 days.
- *Ecotoxicity* – The product must have less than 50 percent of the maximum allowable concentrations of certain metals regulated by law in sludge or composts, and the test compost must be able to support germination of two different plant species at a rate at least 90 percent of that in a “blank” compost control sample.¹⁰

Note the significance of a time factor underlying concepts like biodegradation and composting: materials said to be degradable must actually degrade over a *reasonable time* to qualify. A plastic that degrades in, say, 100 years is not really degradable in any meaningful sense. Indeed, the Federal Trade Commission (FTC), which recently updated its Green Guides for environmental marketing claims, has restricted statements of biodegradability on products and packaging to a period considered “reasonable” by most laypersons: about a year.¹¹ (Bioplastic labeling is discussed in more detail later in Part I.)

The important point is this: from a purely technical standpoint, determining the actual physical characteristics of products and packaging and the way they break down over time – and thus the implications for recovery – is anything but simple. But for most consumers, a general understanding of the difference between biobased and biodegradability may suffice, *if* those consumers are sufficiently informed to place recoverable items in the proper bins.

Production and Manufacture of Bioplastics

With key terms defined, this section explains bioplastic manufacturing and includes a discussion of emerging markets and producers of these materials. A wide variety of bioplastics is being developed or already has been commercialized, but the current market is dominated by a few types. Our discussion here centers mainly on bioplastics used in packaging, with particular focus on California and U.S. producers and the resin types highlighted in red in *Figure 2*.

Bioplastics derived from starch

Starch is a type of bioplastic obtained directly from ingredients readily available in common vegetable crops such as corn, wheat, and potato. Plants naturally make starch, which is a

^{##} ASTM Standard Specification 6868 establishes similar requirements for plastic-coated paper and related packaging. Other standards-setting organizations also have developed specifications for compostable plastics or packaging. Notably the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) have established compostability standards similar to those by ASTM (EN 13432 and ISO 17088, respectively), but with certain differences. At the time of this writing, ASTM D6400 was under review for possible amendment.

carbohydrate primarily composed of linear amylose and branched amylopectin molecules. These molecules form small granules that can be used as a feedstock to make starch bioplastics.¹²

Native starch does not exhibit sufficient plastic performance properties, so it needs to be modified to become a useful thermoplastic material. Starch is heated and combined with plasticizers, most commonly glycerol, citric acid, and water, to form starch composites called thermoplastic starch (TPS).¹³ Resin made of TPS can be extruded into foams and solid molded products. However, these items have performance challenges as they tend to become brittle over time and disintegrate when exposed to water.

The performance properties can be improved by blending TPS with other polymers, such as PLA, polycaprolactone (PCL), and polyhydroxybutyrate (PHB).^{14,15} TPS blends have been used to manufacture plastic bags, food packaging, disposable tableware, agricultural film, and many other items.¹⁶

The PHA clan

The second noteworthy category of bioplastics is the family of polyester polymers called polyhydroxyalkanoates (PHAs). PHA polymers are built by linking long chains of identical, small molecules called monomers. Slight differences in the chemical make-up of these monomers determine the type of polymer they produce. PHB – the bioplastic under development at Stanford and discussed in this report – is a naturally occurring energy storage molecule found in certain types of bacteria. PHB exhibits similar physical and performance properties to polyethylene (PE) and polypropylene (PP), which are used in many consumer products.¹⁷

Several features of PHB and all polymers in the PHA family make them attractive for packaging:

- they are strong, malleable thermoplastic polyesters,
- they can be produced from renewable feedstocks,
- they are compostable and biodegradable in marine environments (under specified conditions), and
- they are relatively non-toxic.

Polyhydroxyvalerate (PHV) is a similar PHA polymer under development for packaging applications, but distinct from PHB. Both are thermoplastic polymers, capable of being shaped and molded into any desired form when they are heated. However, the various PHAs exhibit slight differences in physical properties, such as stiffness and viscosity, making each more or less appropriate for different plastic products.

PLA

Probably the most widely known packaging bioplastic in the U.S. is polylactic acid or polylactide (PLA). It can be produced from various sugars, including those derived from corn, which are fermented naturally to produce lactic acid. The lactic acid molecules are further processed synthetically using a catalyst to produce lactide rings, which in turn are polymerized into long chain molecules. The polymer is then formed into pellets that are sold to product manufacturers.¹⁸ PLA is suitable for a wide range of products, including beverage cups, food containers and packaging, electronics, films, clothing and nonwoven fabrics. One analysis pegged global PLA

packaging tonnage at more than 50,000 metric tons in 2010, nearly twice the next largest category, starch-based bioplastics.¹⁹

Biobased PET

Bio-derived PET has gained significant market share recently, coinciding with Coca-Cola's expanded production of its PlantBottle™, which uses PET sourced in part from ethanol made from sugar cane. Introduced in 2009, the PlantBottle substitutes cane-derived monoethylene glycol (MEG), one of the main constituents in PET, for its petroleum-based counterpart. The biobased MEG makes up about 30 percent of the PET in the PlantBottle; Coke and its partners are working to develop renewable sources for terephthalic acid (TPA), the remaining 70 percent of PET.²⁰ The key feature of the PlantBottle is that it is chemically identical to traditional PET, and therefore can be recycled in existing recovery systems. It is not biodegradable. (We discuss the recycling implications of the PlantBottle in Section II.)

Manufacturers and market trends

Numerous market reports in recent years predict strong growth in bioplastic demand worldwide. For example, a 2012 assessment by market research firm Smithers Rapra projects a global compound annual growth rate of 25% for all bioplastics through 2017.²¹ A 2013 industry-funded survey by the German firm nova-Institute found 247 companies producing biobased polymers worldwide, and projected biopolymer production capacity will triple by 2020 when compared to the amount produced in 2011.²² Packaging makes up a significant portion of bioplastics demand, with another study projecting growth in packaging applications to increase to 383,000 metric tons by 2015, up from about 125,000 metric tons in 2010.²³

Still, bioplastics currently make up a small portion of all plastics produced. But their share seems likely to increase. A number of market drivers are pushing demand, especially in Europe and other regions. These include:

- Consumer concern for the environment, or “green culture”
- Sustainability initiatives by brand owners and retailers
- New technologies, including the recent commercialization of plant-based polyethylene
- New technical standards, regulations, certification programs and labeling systems
- The price and availability of crude oil
- Government programs, including market development initiatives for biobased products, and
- The development of industrial composting facilities that can accept compostable packaging.²⁴

In the U.S., demand for bioplastics lags behind that of Europe, but growth is nevertheless strong. Several North American producers are especially relevant to the California market. Table 2 lists several of these, with details following the table.

Table 2 - Selected U.S. and California Bioplastics Manufacturers

Manufacturer	Feedstock	Plant Location	Brand Name	Polymer	Target Packaging Applications
NatureWorks LLC	Corn	Blair, NE	<i>Ingeo</i>	PLA	Bottles, bags, food serviceware, cups, tubs, cartons, clamshells
Cereplast Inc.	Starch from corn, tapioca, potato; algae.	Seymour, IN (HQ in El Segundo, CA)	<i>Cereplast Compostables, Biopropylene, others</i>	Starch-PLA blends, others	Clamshells, food serviceware, cups
Metabolix Inc.	Corn	Leon, Spain (HQ in Cambridge, MA)	<i>Mirel, Mvera</i> (films)	PHA	Bags, food serviceware, lids
Mango Materials	Methane	Palo Alto, CA	---	PHA	Bottles, food packaging, other
Newlight Technologies	Methane, carbon dioxide	Irvine, CA	---	PHA	Film, containers, other packaging
Micromidas	Cellulose from cardboard	West Sacramento, CA	---	paraxylene (precursor for Bio-PET)	PET bottles, packaging
Meredian, Inc.	Plant-based fatty acids	Bainbridge, GA	<i>Meredian PHA</i>	PHA	Food serviceware, films, other packaging, nonwoven fabric

NatureWorks

NatureWorks is by far the largest bioplastics producer in North America – and the largest in the world – with a plant capacity of more than 300 million pounds (about 140,000 metric tons) of PLA per year at its Nebraska plant. In addition, NatureWorks has announced a \$150 million investment in the company by Thailand’s largest chemical producer, PTT Chemical Public Company Limited (PTT Chemical). NatureWorks plans to build a second manufacturing plant in Thailand of similar size to the U.S. facility, with a tentative opening date of 2015.²⁵

The company produces corn-based PLA at its U.S. plant, but has plans to use sugar cane in Thailand. Long-term, NatureWorks plans “second-generation” PLA derived from cellulosic materials. It has also formed a joint venture with BioAmber, Inc. to expand its product line with blends of PLA and biobased polybutylene succinate (PBS).²⁶ And in June 2013, the company announced a research and development partnership with Calysta Energy of Menlo Park, CA (near Stanford University) to explore methane as a feedstock for producing lactic acid.²⁷

Cereplast

Cereplast, the second largest producer of bioplastic products in North America, manufactures a line of starch-based and blended resins for packaging applications. They are sold under brand names like *Cereplast Compostables* and meet standards for compostability in the United States and Europe. Founded in 2001 in El Segundo, California, Cereplast had a manufacturing facility in nearby Hawthorne, but closed that plant in 2010. Its current plant in Seymour, Indiana has a capacity of 80 million pounds (more than 36,000 metric tons) per year.²⁸

Cereplast specializes in starch/PLA blends, as well as blends of petroleum-based resins with compatible biobased polymers. Its starch-based resins are derived from food crops like corn and potatoes, and more recently the company has commercialized “Biopropylene,” a bioplastic made partially from algae.²⁹ In 2013 the company created a wholly owned subsidiary, Algaeplast™, Inc. to further develop algae-based plastics with up to 100 percent algae content.³⁰

Cereplast has been aggressively pursuing the European market for film plastic in the wake of Italy’s new law banning traditional plastic bags in favor of those made from compostable materials.³¹ In 2011, the company created a subsidiary, Cereplast Italia SPA, and completed purchase of a manufacturing plant in Italy. It will refurbish and expand the facility, eventually reaching an annual production capacity of about 200 million pounds (more than 90,000 metric tons).^{32, 33}

Cereplast sponsored a contest to design a generic bioplastics symbol to be “used in a similar fashion to the recycling symbol, as it will be stamped on products, and it will serve as an identifying mark of bioplastic material,” according to Cereplast CEO (and founder of the Biodegradable Products Institute) Fredric Scheer.³⁴ More than 1,500 entrants submitted drawings. Design student Laura Howard won the \$25,000 prize with the logo in *Figure 3* below:



Figure 3 - Winning logo design in Cereplast contest (copyright permission pending)

Unveiled for Earth Day 2011, the company hopes the symbol will become universally recognized, much like the 1970s-era chasing-arrows recycling symbol that inspired the contest. At press time Cereplast was in the process of securing trademark protection for the logo.³⁵ (Using the symbol to label products is not without critics; we discuss labeling considerations later in Part I.)

Metabolix

Metabolix is a Cambridge, Massachusetts based biotechnology company founded in 1992 by Oliver Peoples, a former research scientist with the Massachusetts Institute of Technology (MIT). The company focuses on the biobased production of energy and chemicals as well as the manufacture of bioplastics in the PHA family. Its *Mirel* line of bioplastics uses a proprietary fermentation process involving genetically engineered microbes. Feedstocks include sugars from corn and other agricultural products, with a long-term goal of converting to cellulosic and other non-food materials. *Mirel* meets ASTM and European compostability standards, and some versions have U.S. Food and Drug Administration (FDA) food-contact approval.³⁶

Metabolix has received substantial research and development monies from the U.S. Departments of Energy, Commerce and Agriculture (USDA) and from the Canadian government to accomplish various goals. These projects included development of a model biomass biorefinery for producing polymers and energy, and seed money to develop *Mirel* grades suitable for blow-molding bottles on a commercial scale.^{37,38}

In a joint venture with Archer Daniels Midland (ADM) named Telles, Metabolix in 2010 opened a 110-million pounds per year manufacturing facility in Clinton, IA, potentially making it the world's largest producer of PHA bioplastics at the time. However, the plant faced a number of hurdles, including a lawsuit by neighbors complaining of odors and other nuisances.³⁹ ADM withdrew from the partnership in February 2012, effectively terminating new resin production. It cited uncertain financial returns as the reason for dissolving the relationship. Metabolix retained the remaining product inventory (about 5 million pounds) and all intellectual rights to the technologies.⁴⁰

As of this writing, Metabolix continues to explore other options for commercially producing its PHA polymers. In 2012 the company signed an agreement with Antibióticos SA, a toll manufacturer based in Spain, to produce *Mirel* on a demonstration scale. However, by the end of that year the arrangement became uncertain as the Spanish company began financial restructuring. Metabolix acknowledged its "ability to obtain biopolymer product from Antibióticos will depend on the outcome of that restructuring."⁴¹

Mango Materials

Mango Materials is a Redwood City, CA startup company developing PHB using technology based on intellectual property licensed from Stanford University. (The Stanford process is discussed further below.) Mango uses waste methane generated at landfills and wastewater treatment facilities as a feedstock. The company converts the gas into plastic by feeding it to methane-eating bacteria, known as methanotrophs, who metabolize it through fermentation into PHB. The PHB is then extracted from the cell biomass and converted to bioplastic pellets, ready to be made into a plastic product.

Mango has a partnership with the South Bayside System Authority wastewater treatment facility in Redwood City to supply methane for their research. Founded in 2010, the company won a significant award from the Dutch Postcode Lottery Green Challenge competition to further develop its business. As of this writing, Mango was still in the "scale-up" phase and had not yet produced bioplastic in commercial amounts.⁴²

Newlight Technologies

Newlight is another California company producing bioplastics in the PHA family, using carbon dioxide and methane sourced from wastewater treatment facilities, landfills, anaerobic digesters, and energy-generating facilities. Newlight uses a proprietary biocatalyst derived from microbes, rather than fermentation, to convert the gases into plastic.

Founded in Irvine in 2003, Newlight appears to have significant financial backing, and ten patents for its technology. In October 2012, Newlight announced expansion of a production facility capable of producing 100,000 pounds per year of PHA.⁴³

Micromidas, Inc.

Micromidas, based in West Sacramento, CA, was founded 2009. The company originally focused on developing a PHA bioplastic using wastewater sludge as feedstock. But currently Micromidas is developing a biobased polyethylene terephthalate (PET, the plastic used for water bottles and many other products). It uses corrugated cardboard as feedstock for a chemocatalytic process (chemical transformation) to produce paraxylene, a building-block chemical for PET. Reportedly the Micromidas process can also convert the cellulose in rice hulls, spent brewer's grains and other waste products into glucose using acid hydrolysis. Using a catalyst and heat, the company then converts the glucose into various biobased chemicals. As of this writing, Micromidas is commissioning a pilot plant to produce paraxylene in West Sacramento. The company has raised at least 20 million dollars since its inception.⁴⁴

Back2Earth Technologies

Back2Earth Technologies (B2E), also in California, utilizes a biorefinery system capable of handling packaged or raw organic wastes, converting them to various products including PHAs. B2E's production of PHA uses a proprietary method involving bacteria in anaerobic digestion of food waste combined with recycled water. The result is a powdered PHA resin sold to end users. B2E also licenses its technology to facilities such as food processors and composters, integrating its model into existing sites.⁴⁵

Meredian, Inc.

Meredian in 2012 announced construction of the largest PHA production facility in the United States and perhaps the world, in Bainbridge, Georgia, with a capacity of 91,000 metric tons per year of PHA. (The company's pilot plant was producing about 14,000 metric tons annually at the time.)⁴⁶ It produces the bioplastic from plant-based oils (fatty acids), which are then metabolized by bacteria in a fermentation tank. The fermentation bacteria are found in soil and are not genetically modified, according to the company.

Meredian began in 2007 when its founder purchased rights to a technology developed by Procter and Gamble to produce a type of PHA copolymer trademarked as Nodax. Financing to commercialize the product has come through investors and U.S. government support. The target markets for Meredian's PHA include food utensils, cups and takeout containers; containers for liquid products such as personal care items; plastic film for packaging; and nonwoven fabrics for personal care applications.⁴⁷

The Stanford Process: Converting Waste to Bioplastic

The discussion so far illustrates two important points: there is growing interest in a broad array of technologies that could move us away from petrochemical plastics, and markets for the polymers produced by those technologies are evolving rapidly, often in unforeseen ways. Critical to both of these factors is feedstock. Food-crop sources like corn seem to be leading the pack in this young market, but they are not without controversy. For example, critics assert biobased products derived from food crops – notably corn ethanol – are contributing to price volatility and food shortages worldwide.^{§§}

But some manufacturers and researchers have asked, “What if bioplastics could be produced from waste products?” Stanford University researchers have been investigating the potential of creating a biodegradable PHB polymer using waste methane produced by landfills, wastewater treatment plants or anaerobic digestion (AD) facilities. This is referred to as the *Stanford Process* in this report.

In theory, such a bioplastic could be produced near the source facilities, made into products, and ultimately recovered again in a “cradle to cradle” loop.^{***} Whether theory can become reality is a complicated question, especially the notion of cycling methane through manufacturing and recovery at the end of a product’s life. It was just such a question in 2008 that prompted the California Department of Conservation, Division of Recycling (now part of CalRecycle) to fund Stanford University in a multi-faceted research contract.⁴⁸

The goal was to develop a methane-based PHB in the laboratory and see whether it could be taken to pilot scale, demonstrating the potential for a commercial bioplastic suitable for bottles and other packaging. Just as important, the Department funded Stanford to study potential pathways to recover used PHB and other bioplastics. The goal of this was to see whether both production and recovery of the material could be accomplished in the same facilities, perhaps in small regional plants around the State.

Figure 4 depicts a conceptual model for producing and recovering PHB bioplastics made from waste methane using the Stanford Process. Methane would be captured, made into PHB, and manufactured into products and packaging, which would be used by consumers and then recaptured at the end of the products’ life. The recovered products and packaging would then be turned into feedstock all over again, using anaerobic digestion and other technologies to “de-polymerize” and otherwise break them down to their chemical constituents.

^{§§} For example, in 2013 lawmakers in California introduced a bill (Assembly Bill 278) to require the California Air Resources Board to take into account the effect on global food supplies when calculating the carbon intensity of biobased fuels. (Barry, 2013)

^{***} “Cradle to cradle” is a concept whereby industrial processes mimic nature by recycling feedstock materials in an endless loop, and any “waste” produced becomes feedstock for a subsequent process. The term was popularized by William McDonough and Michael Braungart in their 2002 book, *Cradle to Cradle: Remaking the Way We Make Things*.

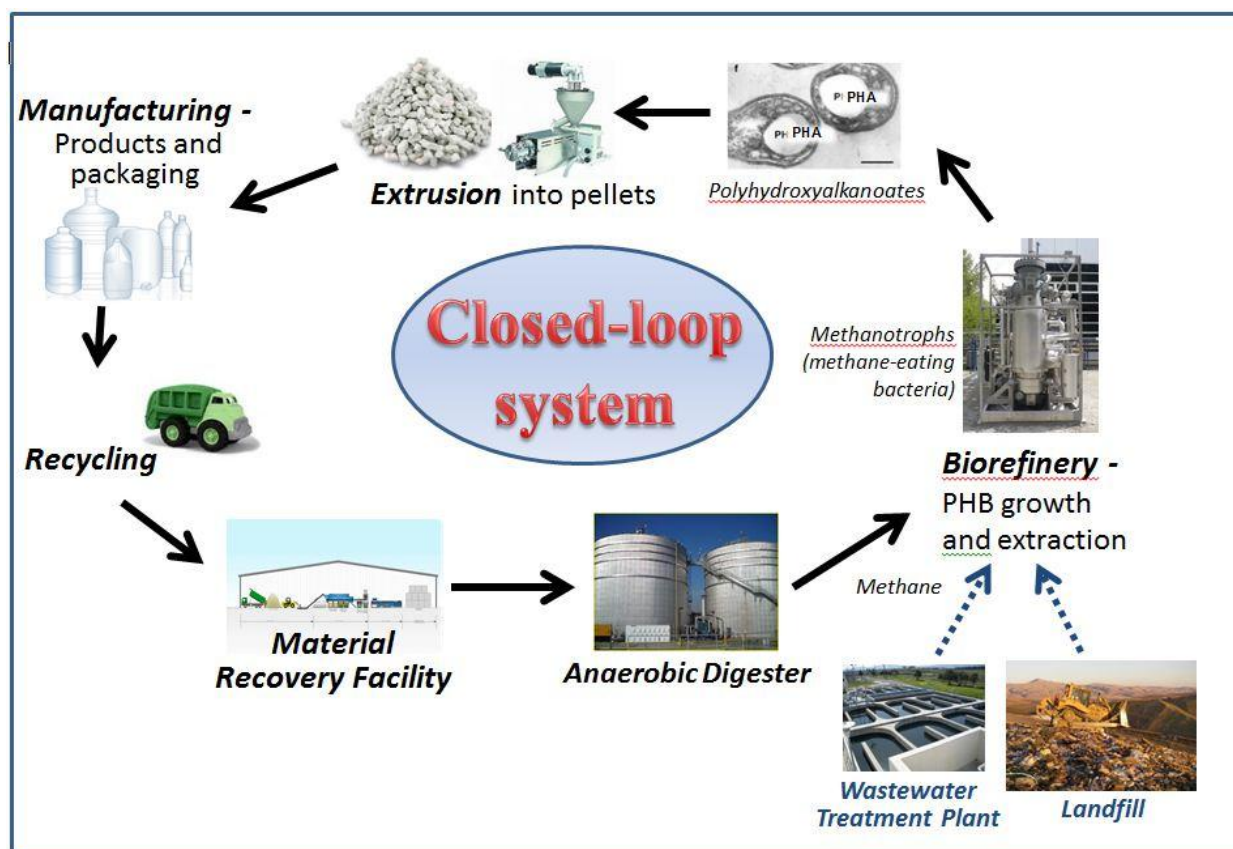


Figure 4 - Conceptual system for producing and recovering PHB from methane.

Charting new territory

The Stanford study set out to harness bacterial strains found in nature – as opposed to using genetic engineering methods favored by some manufacturers – to create a polymer. The team planned to feed methane to bacteria proven to consume the gas (called *methanotrophs*), which in turn would metabolize it into the bioplastic polyhydroxybutyrate (PHB). PHB is a naturally occurring energy storage molecule found in certain types of bacteria. It is readily broken down by microbes in the process of anaerobic digestion, yielding biomass and methane suitable for starting the process all over again.

The researchers established a number of steps to maximize the production of PHB. These included:

- identifying the best methanotrophs for PHB production,
- establishing operating parameters and nutrient levels to maximize PHB production in bench-scale bioreactors,
- determining the most effective and least toxic method to extract the polymer from the bacteria, and

- defining the physical and performance properties of the PHB produced for plastic applications.

The most critical and challenging task for the Stanford team was to identify productive methanotrophic bacteria and to determine efficient operating conditions for their sustained production. Essentially the researchers took an approach to examine naturally occurring bacterial colonies, understand the conditions involved in their growth cycles, and apply that knowledge to optimize the factors leading to maximum PHB production.

Methanotrophs are divided into different types. Stanford selected Type I, Type II, and Type X methanotrophs as the most likely candidates for PHB production. In addition to obtaining pure cultures from other labs, cultures were enriched from numerous sources, including aerobic wastewater treatment plant sludge. Tests clearly showed Type II methanotrophs (especially from the *Methylocystis* and *Methylosinus* genera) were capable of producing PHB, whereas Type I and Type X did not yield any polymer. Once Type II methanotrophs proved to be the superior bacteria, the researchers developed parameters to test for optimal growing conditions. These included determining nutrient concentrations and selection pressures required for a bioreactor to grow maximum yields of PHB. The team developed a micro-plate screening method to quickly and efficiently test many different methanotroph strains and PHB growth conditions and determine the most effective levels of nutrient concentrations. They found calcium and copper to be the most important element nutrients to increase PHB production in the Type II methanotroph *Methylocystis parvus* *OBMP*. PHB production reached 3.43 g/L in the test vessels under the optimized conditions.

They also identified the test conditions required to prevent other microbes present in the bioreactor from dominating the desirable methanotrophs. (Each type is capable of thriving under certain conditions and suppressing the viability of other types. For example, Type I methanotrophs, under certain conditions, can replicate faster than those of Type II, thereby diminishing the ability to produce PHB in a bioreactor.)

Making progress

Stanford found the most important factors to encourage the growth of Type II methanotrophs and select against Type I and Type X methanotrophs included growth under nitrogen fixation conditions, a low pH in the bioreactor, the absence of copper, and use of dilute mineral salts in the growth media. Although these factors helped select for Type II methanotrophs, they were found to either become unstable over long-term use or have negative impacts on growth rates, since they slowed the metabolic capacities of Type II methanotrophs.

The Stanford researchers sought to determine selective conditions that would not slow PHB production. The solution was found by cycling different nitrogen sources for specific periods of time to provide selection pressure and support adequate growth. The bacteria were first fed ammonium, a nitrogen source that can only be utilized by Type II methanotrophs, to select against the competing methanotrophs. Then the nitrogen source was switched to nitrate, which could support rapid reproduction of the PHB-producing bacteria.

Then, in order for the Type II methanotrophs to produce PHB, methane gas must be present and all nitrogen sources need to be absent. Stanford found that by limiting the amount of methane when ammonium is the nitrogen source, a subsequent cycle with limited amounts of nitrate and excess methane produced the most PHB – the methanotrophs consumed all available nitrate

molecules for cell reproduction, then switched to PHB production when the nitrate was exhausted.

The Stanford team also found methanotrophs may utilize PHB for different purposes than most PHB-producing microbes. The researchers theorize the methanotrophs use PHB to facilitate reactions that allow the bacteria to quickly access carbon from methane and take up required nutrients for reproduction. (Other PHB-producing microbes use PHB as a direct source of carbon for growth when methane is not present.) Optimization of the methane/nitrogen cycling events potentially could maximize the production of PHB resin while maintaining a strong and pure population of Type II methanotrophs.

Extracting the goods

Perhaps the most important step in PHB production, from both a green chemistry and cost perspective, is the method of *extraction*, meaning recovery and purification of the PHB material from the methanotrophs. Extraction of the polymer from the biomass is typically an expensive and inherently toxic process, since halogenated organic solvents such as chloroform have been the most widely used method of recovery in commercial operations.⁴⁹ Stanford researchers, aware of these challenges and by direction from CalRecycle, sought alternative methods for extraction that would be cost-effective, reduce toxicity of production chemicals, and maintain the integrity of the polymer quality (high purity and molecular weight).

Tests using supercritical carbon dioxide (CO₂) and a combination of a surfactant (sodium dodecylsulfate, or SDS) and a solvent (hypochlorite) produced promising results. Supercritical CO₂ is an attractive material for extraction because it has no associated toxicity. However, it requires the CO₂ to be kept at elevated temperature and pressure, which confers both a higher cost and potential physical handling hazards for technicians. Early tests with supercritical CO₂ revealed it was effective at purifying the polymer of residual cell biomass, but it did not adequately separate the polymer from degradation products and/or additives found in the bacterial cells.

However, the use of SDS and hypochlorite proved to be a viable method to recover PHB. SDS essentially scrubs and breaks the cell walls of the methanotrophs. Once the cell contents are lysed (broken down), the PHB polymer is dissolved into the hypochlorite, leaving behind residual biomass. The polymer is then separated from the hypochlorite by cooling the solution and precipitating out the polymer. The SDS-hypochlorite method balances the need for an effective, low-cost recovery process with one that minimizes contamination and polymer degradation. A drawback to using this method, however, is that hypochlorite is a chlorinated solvent that requires proper residuals management to control environmental impacts.

Once the PHB polymer is extracted and purified, it can be compounded and pelletized by plastic converters for a wide variety of end-use applications. Stanford researchers tested several potential uses for PHB, identifying areas of strength as well as challenges in using the polymer as a replacement for consumer packaged goods and construction materials. Products addressed in the study included blow-molded bottles, foam insulation and PHB-fiber composites for wood products.

The team paid special attention to performance attributes for both the in-service (consumer use) and out-of-service (composting or other disposition after use) stages of the product lifecycles, bearing in mind potential improvements to desirable properties. PHB can be challenging to

product development because it is brittle and tends to crack. Stanford found ways to reduce brittleness in PHB products by

- increasing the size (larger molecular weight) of the polymer,
- utilizing a co-polymer of PHA such as PHBV, which combines monomers of butyrate and valerate in the polymer chain, and
- blending PHB with a different bioplastic, such as PLA.

Such changes and additions will expand the physical and performance properties of the PHB resin for plastic converters, resulting in improved end-products. (Note performance enhancements can have consequences for recycling and composting, discussed in Part II.)

One of the outcomes of Stanford's research has been multiple patents for the technological advances developed to convert waste methane into bioplastic. While the patents protect the intellectual property of the research team, they also allow licensing to provide entrepreneurs the opportunity to commercialize PHB production and ultimately create products. Appendix A lists the patents filed as a result of the research.

Limitations to Stanford's research

The Stanford team encountered several barriers that will have to be overcome to commercialize the methane-to-PHB process. First, the researchers were unable to sustain growth of Type II methanotrophs and PHB production for long periods of time. Under optimized conditions of limited methane and alternating nitrogen sources, the bacteria were maintained for 37 days, but then the population suddenly crashed (possibly due to toxic levels of hydroxylamine from using ammonia as the nitrogen source). Future work will need to develop a balanced supply of nutrients to sustain production of significant quantities of PHB.

Second, the researchers were not able to find a low cost, low environmental impact method to extract PHB from the methanotrophs. The best method (using a surfactant and a chlorinated solvent) requires significant residual management to mitigate potential harm to the environment.

Finally, the project did not progress from the laboratory to a pilot phase; Stanford was unable to prove the technology could be sustained under optimized conditions at commercial scale. Although a fluidized bed reactor was found capable of producing PHB on a large scale, this method greatly slowed production rates, making it commercially unfeasible. Despite this, Mango Materials, a private company, continues to refine the Stanford process; its additional proprietary technology is not available to CalRecycle.

Up to this point, this discussion has focused on how bioplastics are made and on the potential for these new materials to change the way we manufacture and package goods. But the back end of production is equally critical, and thus it is important to ask "How can it be recovered?" before evaluating the costs and benefits of bioplastics. For the Stanford Process, recapturing the feedstock embedded in PHB products is essential for the model to succeed. And so CalRecycle funded complementary research in which the Stanford team explored end-of-life options for the polymer they were developing, as well as for PLA. Section II addresses the challenges and opportunities surrounding recovery of Stanford's PHB and other bioplastics.

But this section first turns from the technology of producing bioplastics to three other key elements: the economics of production, converting biobased resin into products, and implications for public health. A full discussion of these topics is beyond the scope of this report. Instead, this section summarizes several studies funded by CalRecycle to explore relatively narrow aspects of the subjects. Though limited in scope, they nevertheless bring to light a number of lessons for bioplastic production in California.

California Market Feasibility and Production Costs

Because of the evolving nature of packaging materials and potential environmental and economic issues associated with bioplastics, CalRecycle funded three cost studies of proposed models for producing PHA in California using waste. The intent was to assess the financial barriers and opportunities for such plastics, and more broadly to assess whether such innovation is possible without disrupting existing successful systems for recovering materials. As California moves towards its new goal of 75 percent recycling, evaluating the advantages and disadvantages of promising new uses for what used to be called “waste” takes on even greater significance.

Putting aside for a moment the unintended consequences of new materials in the marketplace (discussed in Section II of this report), bioplastics *in theory* may help meet rising demand for packaging and products with lower potential environmental burdens. As previously discussed, analysts forecast strong growth in global demand for biopolymers in the coming years.

California companies may be able to tap this demand given the right conditions. Indeed, several companies mentioned in this report are doing just that. A closed loop system like the one envisioned for the Stanford PHB process theoretically could both boost economic growth and improve California’s environment by converting waste into a valuable product. And this entire loop could take place within State borders.

But introducing a new material into commerce is anything but simple. Moving from laboratory to pilot scale to full commercialization can take many years and substantial investment. Investors speak of the “Valley of Death” that must be crossed between the germ of an idea and market success, where financial resources are scarce and adequate revenues have not yet begun to flow into a startup company.⁵⁰ Even funding a study of the basic feasibility of commercializing a new technology can be difficult.

In order for bioplastics to compete against established petroleum-based resins – or any other material they might replace – new polymers have to address key drivers that will determine consumer acceptance, especially price and performance. Even environmentally motivated consumers are unlikely to buy a new product if it does not perform as well as competitors or the price is too high. The producer of new materials must stay within these boundaries while simultaneously constrained by the costs of acquiring feedstock, paying employees, operating a plant and so on.

Three angles on cost

Against the backdrop of this emerging market, CalRecycle sponsored bioplastic economic research at three California universities:

- Stanford researchers examined the cost of producing methane-based PHB, using data emerging from the Stanford laboratory research to model chemical and biological processes.

They extrapolated costs to a relatively small or medium-sized plant which could be co-located at regional sites near landfills or wastewater treatment facilities.

- UC Berkeley also modeled a small-output plant using the Stanford process, but took it to the next level: researchers evaluated the feasibility of building and operating a PHB plant from a statewide perspective, collecting data on actual methane availability at prospective sites in California and performing sensitivity tests on critical cost drivers.
- In contrast, UC Davis researchers hypothesized a large plant that would produce millions of pounds of resin per year. Instead of extrapolating costs from the Stanford process, they modeled a facility that would create PHB using residual organic waste from material recovery facilities (MRFs) and otherwise destined for landfill – a key material identified by CalRecycle as critical to achieving the State’s ambitious new recycling targets.

There are inherent challenges in modeling emerging technologies. The newness of bioplastics means there are limited public data on equipment required, production yields, energy demand and so on. Consequently, there is greater uncertainty in estimating the costs of these elements. Recent wide fluctuations in prices for virgin and recovered plastics add to the difficulty. And to the extent technologies have only been demonstrated at the laboratory scale – or may even be untested conceptual models – economic estimates should be treated with caution.

Nevertheless, the university projects described here highlight key economic dynamics surrounding bioplastics in California. Coupled with our evolving grasp of the challenges these materials can impose on existing recycling and composting systems, the research suggests topics for continued inquiry. Below we provide brief overviews of the three efforts and some key findings.

The Stanford Process PHB cost study⁵¹

The Stanford team calculated the cradle-to-gate costs for PHB production (that is, the costs of manufacturing PHB to the point of pellets ready for sale to end-users). The researchers examined waste methane as a possible feedstock from biogas generated at wastewater treatment plants (WWTFs) and landfills in California. Biogas generated at these facilities is commonly used to produce electricity, so they also analyzed the costs of electricity for comparison.

The price of feedstock is a major component of the total cost for manufacturing plastics. The Stanford team hypothesized inexpensive waste biogas may improve the cost profile for PHB production. Since PHB currently costs two to three times more than functionally similar petroleum-based plastics, reducing overall production costs would make it more competitive in the marketplace. So waste biogas generated at WWTFs and landfills may provide a consistent and cheap source of methane to produce PHB using Stanford’s technology. The team noted an added benefit: in theory the PHB essentially could sequester the carbon in a closed-loop system (assuming PHB products are recycled), reducing the greenhouse gas emissions typically associated with WWTFs and landfills.^{†††}

^{†††} During the course of Stanford’s research, California initiated its cap-and-trade market for carbon emissions, part of the state’s climate change initiative. Determining its effect on methane prices, if any, was beyond the scope of both the Stanford and U.C. Berkeley cost studies.

The team modeled production costs for PHB made with the technology and processes developed in the Stanford laboratory. Costs were divided into two categories: capital investment required for equipment and the physical plant; and operational costs for labor, utilities, and materials. Start-up equipment included bioreactors (tanks), both for fermentation of PHB-rich biomass and for microbe reproduction; PHB extraction units; processing equipment to purify PHB; and the administrative and analytical supporting facilities required for commercial manufacturing.

The model incorporated the ongoing costs of operating a plant, projecting the electrical consumption from operating the production tanks, extracting the PHB, and powering the facility as a whole. Labor included the number of staff needed to operate facilities of different sizes. Material costs accounted for the chemicals used as nutrients for growth media and reagents for the extraction of PHB from biomass.

The researchers then extrapolated all of these production costs to different plant capacities, ranging from a small-scale facility producing 500 tons of PHB per year to a very large plant generating 100,000 tons of PHB annually. Finally, the team compared total PHB production costs for different plant capacities to current market prices for plastic resins used for similar product applications.

To help estimate potential PHB production capacity, the authors first looked at the total amount of biogas theoretically available at landfills and WWTFs in California. They categorized 98 landfills according to the amount of “waste in place,” biogas flow, and methane content (data for other landfills were not available). Using the methane component of the biogas from these facilities for feedstock, and the methanotroph metabolism parameters determined by the laboratory research, the Stanford researchers estimated most of these landfills hypothetically could support PHB production of 2,000 tons or more per year, and 13 sites could support production of greater than 10,000 tons per year. They also determined that as WWTFs increase biogas production by introducing more organically rich feedstocks like fats, oils, and grease (FOG), use of this biogas for PHB production becomes more feasible.

Findings and limitations

The Stanford team’s investigation of various fiscal scenarios for developing a PHB manufacturing facility produced a number of estimates:

- A small facility producing 500 tons of PHB per year likely would require a \$2,850,000 capital investment, incurring the highest production cost of \$512 per ton. A very large facility manufacturing 100,000 tons of PHB annually might lower the cost per ton considerably, to \$92. However, such a plant would require a substantial equipment investment of more than \$102 million.
- Perhaps more significant, projected equipment and physical plant costs begin to level out at production capacities of about 5,000 tons per year and greater. The model estimated a facility producing 5,000 tons per year would have an annual cost of \$168 per ton, considerably closer to the per-ton annual costs for the largest facility hypothesized than the smallest. This finding is important because it suggests medium-size facilities with lower overall capital requirements may be possible without incurring significant additional costs per ton, when compared to larger facilities.

- The operational cost calculations determined labor represents almost half (48 percent) of the costs for running small plants (less than 2,000 tons per year), whereas electricity becomes the biggest cost factor for plants larger than 2,000 tons per year, at about 40 percent of total operations. The authors noted electricity costs could be mitigated if a percentage of the biogas generated on-site is used for power production.
- Notably, the model suggests producing PHB at medium-sized plants (5,000 tons per year or less) from waste methane may be feasible at a price competitive with common plastics currently in the marketplace. Plants of this size could be sited at existing landfills and WWTFs in California.
- Many California facilities generating biogas already use it to produce heat and electricity. Analyzing the economics of using the gas for PHB production instead, the Stanford researchers found PHB production potentially could generate more revenue than electricity per unit of biogas, as long as PHB sells for more than \$2 per kilogram. At the PHB price current at the time of the study (\$4 to \$5 per kilogram), methane-based PHB could be an attractive alternative to electricity production for some landfill and WWTF operators.

Stanford's analysis of the cost considerations in producing its PHB is a preliminary projection, a "ballpark" estimate for constructing and operating manufacturing plants of varying scale. It is not intended to be a precise measure of the economic feasibility for siting a facility. Critically, the methane-to-PHB conversion yields and other parameters used in the study were based on laboratory results and could have a large impact on actual production costs. The Stanford technology is not yet proven at an industrial scale over time. Nevertheless, it provides insight into the possibilities of capturing enhanced economic benefits for a waste product of this nature.

The UC Berkeley study that follows delved further into the economic possibilities for Stanford's PHB technology, examining potential manufacturing facilities from a somewhat different perspective and digging deeper into statewide biogas availability.

UC Berkeley study of PHB production in California using waste methane⁵²

UC Berkeley first reviewed statewide and global trends for bioplastic production, highlighting barriers and opportunities for their adoption and providing context for the team's California economic modeling later in the report. The analysis included an examination of resins, manufacturers, product categories and production cost factors. The team studied both emerging bioplastic resins as well as traditional resins they might replace, collecting data on pricing, supply, current demand and potential new markets, end-of-life options and other factors impacting commercialization of novel resins.

The researchers next examined the commercial potential for producing PHB using the Stanford process in California. They modeled a small-scale plant producing 1,000 metric tons a year (about 1100 U.S. tons) using methane sourced from landfills or WWTFs. They examined various cost drivers associated with building and operating the plant, evaluating several factors critical to commercialization.

Using CalRecycle's Solid Waste Information System (SWIS), the UC Berkeley team estimated methane sources statewide that could be available to PHB producers, subtracting out methane already captured for energy production or other uses, and estimating potential capture for facilities without collection infrastructure. Since there is no comprehensive database for methane

generated at wastewater treatment plants, the team forecast potential availability using data gathered at individual facilities and from published documents.

The researchers identified several essential characteristics for determining the optimal locations for a PHB plant:

- Facility size (measured in total waste in place or average dry weather flow for landfills and WWTFs, respectively);
- current generation status (whether methane is currently used to generate power, and if so, the percentage of total available methane used);
- the installed power transmission infrastructure and its location;
- current methane capture and the status of any power generation contracts; and
- the volume of excess methane currently captured and flared.

Once they identified feedstock availability and optimal locations in California, the research team estimated the construction and operating costs for the baseline 1,000-metric-ton-per-year plant. Inputs included PHB yield rates and energy requirements estimated by the Stanford researchers, costs for nutrients in the PHB conversion process, costs for extracting plastic from the methanotrophs using sodium hypochlorite, labor, and PHB price. They determined equipment investment based in part on estimates for a hypothetical biorefinery developed by engineers at the California Department of Toxic Substances Control.⁺⁺⁺

With these data points in place, the model then calculated the Net Present Worth (NPW) over a 20-year project lifetime, assuming a discount rate of 6 percent.^{§§§} A positive NPW suggests the project will be profitable.

Finally, the team conducted sensitivity analyses on five important cost sectors, projecting baseline, high and low NPW scenarios for each. That is, they varied the model's inputs using values higher or lower than baseline to assess whether the outputs (results) would change significantly. The five sectors were:

1. Stanford's estimates of PHB yield and energy requirements;

⁺⁺⁺ The DTSC large-biorefinery concept included multiple lines for producing and recycling PHAs and PLA using several inputs. The UCB team started with the DTSC equipment estimates for the methane-to-PHB line, scaling it down for a small plant but then revising the result upward by 50 percent for a more conservative baseline for equipment costs.

^{§§§} Net Present Worth or Net Present Value is commonly used to estimate the profitability of a project over time. In simple terms, it means the total value in today's dollars of all cash inflows and outflows over the period evaluated, assuming a certain annual interest or "discount" rate for capital invested. Or as the UCB study puts it, NPW is "the present value of the net cash flow for each year of the project summed over the project lifetime." The report further explains the discount rate as "an annual percentage value that accounts for the fact that money in the base year is worth more than money in future years due to the opportunity cost of not having the money available to invest (the time value of money), thus enabling the calculation of the 'present value' of future money."

2. energy procurement method and landfill gas collection status;
3. capital costs for equipment, and annual operation and maintenance costs (including labor);
4. extraction costs; and
5. PHB price.

Findings and limitations

The Berkeley literature review found multiple authors predicting “substantial growth” in the bioplastic sector in the coming years, including a projected increase in demand for PHAs of more than 40 percent between 2010 and 2020. The authors note resin prices have been the main barrier so far to more widespread adoption of biobased and biodegradable resins, but prices will continue to fall, spurring bioplastic substitution for traditional resins in an increasing variety of applications. Certain resins will not be compatible with particular end-uses, however. Pure PHA polymers, for instance, are unlikely to capture much of the beverage container market due to their inherent opaque nature and poor carbonation retention.

Turning to the California market potential for PHB production using the Stanford process, the Berkeley researchers found 49 California landfills and 10 WWTFs with enough available methane to operate a plant producing 1,000 metric tons per year. A plant of this size would consume about 2300 metric tons of methane annually, including about one-fourth dedicated to generation of electricity on site to power plant operations. Thus the authors note “it may be possible for captured methane to be used as both the feedstock for PHB production and as the power source for facility operation,” which could lower production costs compared to manufacturers that must purchase organic feedstocks like corn.⁵³

The researchers further elaborate on the economic implications of appropriate site selection:

“...optimal sites are likely to be mid-sized landfills or WWTFs that may or may not currently capture CH₄ [methane] but do not generate electricity and thus are not subject to contractual agreements with local utilities for power generation. Facilities that exhibit these characteristics and have little or no access to installed power transmission infrastructure may have particular interest in the implementation of PHB production. This may offer such facilities a means by which to turn the CH₄ waste byproduct into a value-added product that can easily be transported where power generation requires expensive power transmission capacity.”⁵⁴

So conditions in a number of California locations could exist for a small plant using waste methane to make PHB. Next the UCB team addressed the costs of operating a plant over a twenty-year time frame. The researchers found a 1,000 metric ton-per-year plant would probably be economically viable within the baseline assumptions. Specifically, they found such a facility could have a positive NPV for any PHB price above \$1.17/kg (\$0.53/lb.). They hasten to add there is a great deal of uncertainty in this projection and the model is “highly sensitive” to certain assumptions; nevertheless they conclude, “given reasonable input parameters and conditions it is likely that such a facility would be profitable.”

The UC Berkeley team also analyzed the effects on their results of varying their major modeling assumptions, as described above. They found PHB price and costs of the extraction process exhibit the greatest sensitivity. They note that although the Stanford team had not yet fine-tuned

extraction methods at the time of publication, the model allows for examining costs per unit of PHB produced regardless of the process. In the baseline scenario, extraction costs below \$1.68 / kg of PHB would likely be economically viable; lowering these costs at commercial scale would significantly reduce a facility's overall financial risk.

All of this is still theoretical. PHB made with the Stanford process has not been produced in significant quantities, and a commercial plant has not been built. Both the technology and its economics are in their infancy. The authors take care to point out the inherent uncertainty in calculating costs for a nascent industry, and of extrapolating costs from laboratory findings to commercial scale. They note the possibility that an actual site may not be able to achieve the requisite methane capture specified in the economic model, thereby jeopardizing viability in the real world. Likewise, even though the sensitivity tests accounted for lower-than-expected PHB prices, it could be that sufficient buyers will not be found at any price, leaving a facility with unsold inventory.

Nonetheless many solid waste and wastewater treatment locations around California may be promising sites for a small bioplastic manufacturing plant. The key concept is that small-scale manufacturing does not mean a small chance for profitability. The notion that a successful manufacturing venture must achieve a so-called economy of scale, requiring a huge facility with corresponding large investments, is not necessarily true.^{***} An entrepreneur of modest means, under the right conditions, might turn a problematic waste greenhouse gas into a useful material for manufacturing products and packaging.

UC Davis investigation of PHA production in California using organic wastes⁵⁵

Unlike the UC Berkeley effort, UCD researchers did not analyze the economics of methane-based bioplastic, nor did they limit their investigation to a small plant size. Instead, they developed an economic model to examine the feasibility, optimal size and best California location for a different sort of PHA facility, one exploiting the sugars in organic MRF residues. Organic materials, including those leaving the back end of recovery facilities, constitute about a third of the tonnage entering landfills statewide – a clear target for additional action as California gears up to reach its 75-percent recycling goal.⁵⁶

The authors conducted their research in two parts. First, they reviewed publically available life-cycle assessment literature on PHA production from sugars derived from municipal solid waste, and modeled the environmental burdens and benefits associated with a hypothetical plant using MRF residuals to produce PHA. (See Section II for discussion of the LCA portion of their investigation.)

*** A recent analysis by the Society for the Plastics Industry (SPI) comes to a similar conclusion. In “Development of Biobased Plastics Independent of the Future of Biofuels” (August 2013), the SPI Bioplastics Council argues many bioplastics lend themselves to small-scale production and so would not be tied to large biorefineries producing biofuels such as ethanol. The paper offers the example of Mango Materials in California, which is producing PHB from methane “by co-locating production with a source of stranded biogas, such as a wastewater treatment facility or landfill.”
<http://www.plasticsindustry.org/files/about/BPC/Development%20of%20Biobased%20Plastics%20-%20August%2026%202013%20-%20FINAL.pdf>

Using the inputs and outputs identified in the LCA segment and additional cost information, UCD then created a model to project the parameters for hypothetical PHA manufacturing plants. The team estimated the average total amount and cellulosic fraction of MRF residuals produced in California annually, and mapped the location of each MRF. This involved gathering data from several sources, including CalRecycle's Solid Waste Information System (SWIS) and a 2006 waste characterization report to the California Integrated Waste Management Board.

The PHA production pathway in the model included conversion of the cellulosic fraction to sugars using enzymatic hydrolysis, fermentation using *e.coli* bacteria, and extraction of the PHA with sodium hypochlorite. Data for these processes came primarily from two studies underlying the LCA portion of UCD's research, as well as various sources for costs of chemicals, electricity, labor, transportation, and so on. Using these inputs, UCD developed equations for an "optimization model" to predict the most efficient location and plant capacity for various prices per kilogram of PHA produced.

Findings and limitations

The UCD analysis predicted Martinez, California (in the San Francisco Bay Area) to be the best location for a PHA plant of the type described, though several other locations scored nearly as high. Such a facility would draw on residuals aggregated from surrounding MRFs (but not mixed waste processing facilities or "dirty MRFs," due to a presumed lower quality feedstock).

The model predicted larger facilities would provide the best opportunity for aggregating MRF residuals, with an optimal plant producing about 148 million pounds (67 million kg) of PHA a year. Given the major financial risk in constructing a plant that size, UC Davis examined a smaller facility producing 33.5 million pounds per year. The model suggested such a facility would require a total capital investment of \$330.4 million, with PHA selling at more than \$6.00 per kg. This compares to virgin PET resin selling for around \$2.00 per kg at the time of the research, according to the authors.

The UCD project was constrained by extremely limited data for many of the model inputs. The researchers found only a handful of studies with relevant data to construct the hypothetical PHA plant. The lack of published data required the UC Davis team to make assumptions or "educated guesses" about many data points. For example, they calculated the costs of separating out the organic material in residuals by using sorting costs for other recyclables as proxies.

Many data points are simply unknown; for instance, costs of enzymes used in the process were estimated in part from studies on cellulosic ethanol, which in turn are projections based on technology not fully developed. Likewise, the usable (cellulosic) fraction of MRF residuals can vary considerably, which affects the yield of sugars produced per ton of feedstock. These and many other limitations prompted the authors to declare the "high level of uncertainty should be kept in mind when interpreting the outcomes of this report."

Though the Davis research does not offer the level of confidence that might be found in feasibility studies of mature technologies, it does provide useful insight into the economics of using California's waste materials in novel ways. The authors note aggregation of feedstock at regional facilities may significantly lower costs. The costs of transporting these materials are relatively minor compared to other cost factors like expected PHA yield rates.

If MRF residuals are to be used to create a value-added product like plastic, much more must be known about specific inputs to the process, including effects of contamination in the residuals, the ratio of cellulosic materials to other fractions, yield rates for sugar production and PHA growth, and methods for extracting PHA from the bacteria. Even then, costs likely would need to drop considerably to compete with traditional plastics. In the end, the project underscores the need for baseline data and the complexity of predicting the market implications of untested technologies.

Data gaps, economic constraints

Taken together, what can we learn from these three projects? An obvious common thread is uncertainty. This is a problem for most emerging technologies: accurate economic forecasting demands robust fiscal data to help bring a product to market, but precise cost information is not forthcoming until the product already has been brought to commercial scale.

Thus the CalRecycle-funded research detailed here should be viewed in context. The university research highlights data gaps, areas for further focus as Californians evaluate novel ways to turn waste into an asset. The implications of the economic research are discussed in more detail in Part III, *Lessons Learned*.

Making Products and Packaging with Bioplastics

Once bioplastics can be produced as reliable feedstock material for making products, then what?

Plastic products are ubiquitous. The reason for this lies in the vast array of physical properties different polymers bring to the table. Depending on the formulation, plastic resins are moldable, flexible, floatable, stretchable, unbreakable, gas-impermeable, colorable, durable, foam-able – in short, the end-use applications for plastics seem limited only by the creativity of those who use them.

Bioplastics may be able to substitute for their petrochemical analogs in many of these applications. So-called “drop-in” resins are the Holy Grail of bioplastic manufacturing: they would be capable of replacing, pound-for-pound, the qualities and performance characteristics demanded of traditionally-sourced polymers. Soft drinks, for example, require a material that “keeps the fizz in” for an extended shelf life. This is one reason Coke turned to biobased PET for its PlantBottle™: chemically it is exactly the same resin as in Coke’s proven petro-PET bottles, fully recyclable in the PET stream, but partially produced from different source materials.

Package designers want to ensure their packages perform essential functions. Product protection during shipping, preservation of food or other perishables, safe use by consumers and not least, marketing all factor into design decisions. Each of these has corresponding technical requirements, many standardized by ASTM. The appropriateness of any particular resin for a given application depends on testing for such things as

- *Creep* (the application of a fixed load to a specimen and measurement of resulting deformation over time)⁵⁷,
- *Melt flow rate* (the rate of extrusion through an orifice of specific length and diameter under prescribed temperature and load)⁵⁸,
- *Tensile strength, elongation and modulus* (measurements of a material’s ability to withstand forces that tend to pull it apart, and its stretchability before breaking)⁵⁹,

- *Water vapor transmission* (the rate of water vapor flowing through permeable materials under test conditions and a specified time period)⁶⁰,
- *Viscosity* (a fluid's resistance to flow)⁶¹, and
- *Crystallinity* (a molecular structure characterized by uniform geometric patterns).⁶²

So tailoring a resin to a specific need can be complex. Typically the base polymers alone would not be sufficient to meet required parameters for the qualities above, as well as many others. Whether biobased or petroleum-sourced, polymers by themselves may be too brittle or thick or unstable for finished products.

Additives: performance-enhancing substances

When it comes to polymers, chemicals that enhance performance have their place. Additives can improve both a resin's processability and its ultimate properties, and therefore its suitability for any given application. But some plastic additives are controversial. They may have consequences for human health, not to mention the environment and California's materials recovery infrastructure.

The main ingredient used for manufacturing plastics is the base polymer, such as PET or PLA. But the production of plastic products and packaging involves a wide variety of chemicals in all steps of the manufacturing process, each serving a unique purpose. Plastic converters (manufacturers who "convert" raw resin pellets or other feedstock into finished products) mix additives with base resins or resin blends, typically melting and compounding them (combining them under controlled conditions) in an extruder to make plastic pellets. The pellets then can be fed into plastic manufacturing equipment to be molded or shaped into any desired product, such as bottles or clamshells.

Converters may employ these substances to change the melt flow, reduce polymer degradation, and improve resin performance during fabrication. Additives also may increase a polymer's strength, flexibility, durability, stability, as well as resistance to other chemicals, heat or weather. Packaging manufacturers may employ blowing agents to facilitate bottle blow-molding, colorants to fine-tune consumer appeal, or antioxidants to extend beverage shelf life. The list goes on.

Additives have been used in plastic products for decades. But more recently, inclusion of certain ingredients has raised concern among recyclers and composters about the consequences for recovery operations and material quality. Two types, fillers and degradable additives, have received particular attention for their end-of-life implications. Part II addresses these issues in the context of California's recovery infrastructure.

Bottles and other containers

Bioplastic bottles and other containers can, as discussed above, be produced from renewable resources and have the potential to address significant environmental concerns. Preliminary research described above suggests PHA production in California could be economically viable. But bioplastic containers also can challenge the state's recovery programs that have taken decades to build. A producer introducing bioplastic containers in California enters a mature recovery system developed from several statewide policy directives, including the beverage container recycling program, rigid plastic packaging container (RPPC) requirements, and others.

Bottle project: Cal State Chico

Could a PHA-based bottle fit into this framework? The first step to address that question would be to create a prototype for experimental purposes. (Although some PHA-based bottles have been introduced commercially, little is known publically about their composition.) With funding from CalRecycle, the DTSC contracted with California State University, Chico, to perform experiments with three bioplastic resins to determine if it was possible to blow-mold a high-quality bottle and to identify the best operating parameters for this process.

CSU Chico identified properties and characteristics of various PHA bioplastic polymers and co-polymers that could be used to manufacture bottles. The principal investigator found the most promising PHA polymers available commercially^{††††} that can withstand the bottle making process, utilized certain additives to improve bottle quality, and determined the optimal operating parameters for the bottle-making equipment. Once the bottles were produced, they were for quality and essential performance properties.

To understand the nature of PHA polymers and their performance in standard plastic converting equipment, CSU Chico identified three potential polymer candidates: a PHBV co-polymer produced by the Tianan Biologic Material Company in China, and a variety of PHB called P(3HB-4HB) made by two companies, Tianjin Green Bio Company of China and the *Mirel* resin made by Metabolix.

The principal investigator then designed experiments to test the resins' capability for blow-molding into bottles. Only the *Mirel* produced adequate bottles without special additives. The polymers from Tianan and Tianjin both required additives to improve the melt strength, crystallinity and thermal stability before successful extrusion blow-molding.

He next determined the optimal operating parameters for the blow-molding equipment. Melting points for each of the PHA resins were determined to establish temperature settings for the equipment. The researchers found the Tianan and Tianjin resins could use the same settings, whereas the *Mirel* generally required higher pressures and temperature to optimize production. By adjusting the plastic formulations and operating conditions, he was able to produce a number of prototypes in the laboratory.

To assess bottle performance, the research included both qualitative and quantitative measurements. The team graded each bottle on a scale of 1-5, based on the quality of its form, integrity, and consistency. Key physical and performance properties were then analyzed to assess the bottles' ability to meet product demands for the marketplace. These included:

- melt index (viscosity measured by flow of material),
- tensile (elongation) and impact strength,
- water and carbon dioxide permeability,
- water absorption, and

^{††††} CalRecycle had hoped to include Stanford's PHB, but the team had not yet produced enough polymer for testing at the time of the CSU project.

- scuff resistance.

Overall the Metabolix resin outperformed those from Tianan and Tianjin in its ability to produce a high-quality bottle. The bottles made from *Mirel* scored highest on the quality assessment and exhibited the most desirable performance properties for bottle production.

CSU Chico found PHA is best suited for a one-step extrusion blow-molding process and not for a two-step stretch blow-molding process. Thus, PHA can be shaped into bottles known to use the extrusion process, such as shampoo or detergent plastic bottles. However, the PHAs tested are not as well suited for water or soda bottle applications, as these require the stretch blow-molding process.

As a side project, a few prototype bottles created during the research were introduced into an optical sorting trial during the Future 500 grant project described in Part II of this report. If PHA-based containers do become widespread, it will be important for optical sorting machines or other technologies at MRFs to separate them from other plastics.

Bottles, Take 2

As previously mentioned, Metabolix received a \$350,000 grant from the U.S. Department of Agriculture in 2009 to develop bottle-grade PHA polymers suitable for commercial production. The objective was to bring to industrial scale a drop-in biobased resin capable of replacing HDPE used in bottles and other containers. The project would fine-tune physical properties of the resin like melt strength and crystallization, to allow it to be used on existing manufacturing equipment. Once appropriate formulations were developed, the researchers would attempt to blow-mold bottles, test their properties against commercial standards, and develop optimal production cycles.

However, the Telles joint venture between Metabolix and Archer Daniels Midland dissolved subsequent to the bottle grant award, shuttering the Iowa PHA manufacturing plant as previously mentioned. As of November, 2013, results of the blow-molding research had not been publically released.

But if the status of PHA bottles on this continent is unclear, others are moving forward. In the summer of 2012 an international consortium of European and Latin American companies and research centers launched the “PHBottle” project. Funded largely by the European Union’s 7th Framework Programme for Research and Technological Development, the €4 million research effort joins fruit juice producers with plastic engineers to develop biodegradable PHB bottles, caps, and labels, using the sugars in fruit processing wastewater as feedstock for the resin.

As wastewater treatment is a major issue for juice processors, the project’s goal is to lower costs by turning what is now a wasted resource into an asset, a rationale similar to the concept behind Stanford’s methane-to-PHB research. Coordinated by the Ainia Food Research and Development Center in Spain, the effort also includes packaging and food industry scientists from The Netherlands, Belgium, Portugal, Bulgaria, Brazil, Argentina, Honduras, and Mexico. EU funding continues through October, 2015.

Project activities will occur in three phases. First is to identify the optimal organisms to produce the PHB and then manufacture the basic resin. Next, the researchers plan to introduce cellulose fibers and antioxidant agents to strengthen the plastic and meet commercial specifications for maintaining shelf life and product quality. The final phase will be to blow mold bottles, fill them with juices, and test their performance. Various production methods will be evaluated, including

extrusion blow molding, injection blow molding (for “preforms,” blank plastic tubes that can be blown into bottles onsite or elsewhere), film extrusion (for the bottle sleeves) and standard injection molding (for bottle caps and other applications).⁶³

The effort will include an LCA on the entire process, from raw material acquisition through bottle manufacture and filling to “final disposal.” (It is unclear whether this includes analysis of end-of-life options like composting or anaerobic digestion.) The PHB and its biocomposites will be compared to the competing fossil-based resins PET, HDPE and polypropylene (PP).

Clearly an ambitious undertaking, the PHBottle research indicates a conscious desire by some sectors – with substantial resources – to move away from petrochemical packaging toward a closed-loop system.

Note that bottles made from corn-based PLA have been on the market for several years in the U.S. and in California. At least one beverage company still sells water in such containers in our state. But major beverage players like Coca-Cola and PepsiCo have chosen not to adopt PLA, and the main North American PLA producer NatureWorks is shifting away from the bottle market. PLA bottles are discussed in more detail in Part II, in the section on end-of-life implications of bioplastic containers.

Bioplastics and Public Health

Bioplastics and other new materials are emerging at a time of increased scrutiny of chemicals in commerce and the effects they can have on human health. Indeed, California’s landmark green chemistry legislation arose from just such concerns. Materials science has advanced dramatically in recent decades; the science of public health is struggling to keep pace.

This is not to say knowledge is static on that front. Much research has been devoted to understanding the relationships among chemicals used in plastic products and the many possible pathways of exposure to consumers. Moreover, the science of toxicological risk assessment is expanding as well. Substances previously thought to be harmless may have subtle long-term consequences, particularly for vulnerable groups like children. And new research, in turn, is giving rise to new laws for protecting public health.

Plastics and packaging safety

California’s Proposition 65 is just one of many public health-related mandates that may affect the introduction of bioplastics into the marketplace. That law requires the State to maintain a list of chemicals “known to the State to cause cancer or reproductive toxicity.” A complete discussion is beyond the scope of this report, but a few other laws related to packaging safety are worth noting.

TOSCA sets the national context

At the federal level, the Toxic Substances Control Act of 1976 (TOSCA) broadly regulates chemicals in the marketplace. The U.S. Environmental Protection Agency (EPA) administers the law, identifying potentially dangerous chemicals, gathering relevant information about potential health effects, requiring manufacturers of potentially dangerous chemicals to conduct tests on the substances they produce, and tracking chemicals new to the U.S.

Under TOSCA the EPA may regulate most phases of a chemical’s life, from manufacture through consumer use and final disposal. It can take a number of actions related to the chemicals under its purview, from requiring warning labels all the way to a complete ban of a substance.

By the time the EPA was to issue regulations for testing, there were 55,000 chemicals in U.S. commerce.⁶⁴ Current estimates peg the number in the U.S. marketplace at around 85,000, with about 2,000 new chemicals introduced each year. A number of these have drawn particular attention as “Emerging Chemicals of Concern” (ECCs), including some that may find their way into plastics. Examples include Bisphenol-A (BPA), phthalates (used to soften vinyl products, among other functions), brominated flame retardants, nanoparticles, and various additives and stabilizers.⁶⁵

California steps up: the Green Chemistry movement

While Congress debates the latest TOSCA reform proposals, California has taken the regulation of chemicals – and thus bioplastic packaging formulations and their safety – a step beyond the federal government. As mentioned at the beginning of this report, concern about the proliferation of chemicals in the marketplace led to the California Green Chemistry Initiative (CGCI). The aim of green chemistry is to proactively reduce and prevent toxicity in the *design* of products, at the front end of manufacturing, rather than wait until products are already in the marketplace. The CGCI marks a fundamentally different path to regulating chemicals in products and packaging than the approach in TOSCA: it is *cradle to cradle* rather than *end-of-the-pipe*.

Assembly Bill 1879 requires DTSC to identify chemicals of concern, prioritize them, evaluate safer alternatives, and develop regulatory actions when these chemicals turn up in products. Its companion statute, Senate Bill 509 (Simitian, Chapter 560, Statutes of 2008), requires the agency to maintain a Toxics Information Clearinghouse of data on the toxicity and risks associated with chemicals used in consumer products.

The agency submitted the final “Safer Consumer Products” draft regulations to the Office of Administrative Law in July, 2013, where they remain under review as of this writing.⁶⁶ If approved, the regulations would set up a four-step “continuous, science-based, iterative process to identify safer consumer product alternatives.” DTSC would identify “Chemicals of Concern” (COCs) and prioritize products containing them. Priority Product producers would be required to assess and perhaps adopt less-harmful alternatives to the COCs.⁶⁷

What are the implications for bioplastics? The level of scrutiny a given new material may face in California is currently unknown. Products and packaging made from bioplastics may rise to the level of Priority Products, depending on additives used in production and whether they are blended with other compounds. Or perhaps they may benefit from the new emphasis on green chemistry, embraced as safer alternatives to their petrochemical cousins. A bottle made from naturally occurring PHB, for instance, could be an alternative to its counterpart made from phthalate-containing vinyl.

Food packaging and the FDA

Despite the uncertainty, there is a clear course for companies desiring to package food in bioplastics. To enter that market, they must work with another federal agency: the FDA.

The FDA’s Office of Food Additive Safety regulates industry to ensure food contact substances are safe. The Food, Drug, and Cosmetic Act defines food contact substances as “any substance intended for use as a component of materials used in manufacturing, packing, packaging, transporting, or holding food if such use is not intended to have any technical effect in such

food.”⁶⁸ Examples include plastic packaging materials, pigments and antioxidants used in polymers, can coatings, adhesives, and sealants for lids and caps.⁶⁹

As it relates to packaging, the term “safe” is defined by the FDA as a “reasonable certainty in the minds of competent scientists that a substance is not harmful under the intended conditions of use.”⁷⁰ The agency determines safety through the Food Contact Notification process, which includes review of such items as manufacturing methods, toxicology and chemical migration testing, and likely consumer exposure.

So food packaging is a special case in the nexus between bioplastics and public health. One other area deserves mention. California, like many states, singles out several heavy metals for special attention when it comes to packaging.

California Toxics in Packaging Prevention Act

The Toxics in Packaging law (Assembly Bill 455, Chu, Chapter 679, Statutes of 2003, and amendments) prohibits the intentional introduction of specific substances in packaging sold in the state: lead, cadmium, mercury, and hexavalent chromium. In line with green chemistry principles, the program promotes safer packaging in the design phase rather than imposing restrictions at the end of an item’s life. Manufacturers and suppliers must certify to DTSC their packaging complies with the Act.

A manufacturer who wants to use these metals – say, to make its logo imprinted on a container more attractive to the consumer – is banned outright from doing so, with some exceptions. Moreover, the law restricts “incidental” presence of the metals in a packaging component to less than 100 parts per million.

Truth in labeling

So far this discussion of bioplastics and health has centered on the chemical makeup of products. But there is a related topic, not necessarily the province of chemistry labs, informed by both emerging science and common sense.

Let’s say the Acme Company makes bioplastic trash bags. Acme’s research department commissions soil burial tests to show the product will decompose in the presence of water and oxygen. The marketing department runs with it, embellishing each bag with a simple, unadorned statement: “Biodegradable!” Sound reasonable?

Not according to the Federal Trade Commission (FTC). The agency says the biodegradation claim is deceptive: “Unqualified degradable claims for items that are customarily disposed in landfills, incinerators, and recycling facilities are deceptive because these locations do not present conditions in which complete decomposition will occur within one year.”⁷¹ The scenario above comes directly from the FTC’s *Guides for the Use of Environmental Marketing Claims*, covering terms like *degradable*, *compostable*, *non-toxic*, *recyclable*, and *made with renewable materials*.

The agency may bar a company from marketing a product found to be deceptive. In 2009, for instance, the FTC prohibited the Kmart Corporation for advertising disposable plates as “biodegradable.”⁷² The *Guides* state it is deceptive “to misrepresent... a product or package is degradable, biodegradable, oxo-degradable, oxo-biodegradable, or photodegradable,” and producers must have “competent and reliable scientific evidence that the entire item will completely break down... within a reasonably short period of time after customary disposal,”

defined as one year.⁷³ The *renewable materials* section of the *Guides* has additional examples for bioplastic producers. Moreover, the FTC's separate *Endorsement Guides* provide rules for green certification marks and seals of approval, including disclosure of the basis for certification and the relationship between the manufacturer and the endorsing organization.⁷⁴

Bioplastic producers may find themselves pulled directly into the growing vortex surrounding advertising and the environment. Consumers are wary of misleading claims, the FTC is paying close attention, and brand owners who fail to substantiate their claims risk getting branded with a different sort of label: "Greenwashing," or disinformation intended to present an environmentally responsible public image.

California takes it further

When it comes to claims about degradability, for instance, California has gone beyond the *Green Guides*. California enacted strict regulations in 2008 to address environmental marketing claims for plastic food and beverage containers, which were expanded in 2013 to include all plastic products.⁷⁵

Senate Bill 567 (DeSaulnier, Chapter 594, Statutes of 2011) prohibits the sale of plastic products labeled *compostable* or *marine degradable* unless they meet the applicable ASTM standard specifications for those terms, or the European "OK Compost HOME" certification for the term *home compostable*. Under certain conditions, the law gives CalRecycle some discretion to adopt another standard for home compostability, should ASTM or another organization develop one.

But the law goes further. The legislative findings in SB 567 assert *biodegradable* or like terms only make sense in specific environments and time frames, which are not possible to adequately explain on a label without reference to a "an established scientific standard specification." Since currently these terms have no such standards, the law prohibits their use altogether:⁷⁶

Compostable bags, in addition to meeting compostability standards, must be labeled in a way to make them "readily and easily identifiable" from other plastic bags. The law specifies certain options, including use of a logo indicating third-party certification of compliance with ASTM D6400 and labeling a bag "compostable" combined with a green stripe.

The California Attorney General filed its first "greenwashing" lawsuit in 2011, invoking the state's labeling laws against three companies. The companies were marketing as "biodegradable" and "recyclable" plastic water bottles containing additives designed to break down the resin. The court in 2012 approved settlement with two of the companies, in which they paid penalties and agreed to stop using both the terms and the bottles.⁷⁶

LBNL examines the leaching issue

PET is the package of choice for most bottled water. But by 2009, several companies had begun to market water in California bottled in PET with additives designed for biodegradation, and in

⁷³ Except as allowed with respect to a "compostable" or "marine degradable" claim. The bill allows for eliminating this prohibition if ASTM develops standards in the future.

PLA. Cognizant of the heightened interest in bottled water quality,^{§§§§} DTSC sponsored research into the potential for leaching of plastic constituents into water packaged in PLA and PET. With funding from CalRecycle, DTSC contracted with Lawrence Berkeley National Laboratory (LBNL).

The LBNL researchers quantified chemicals that were present in drinking water packaged in PET and PLA bottles from different manufacturers at different temperatures and storage times. The study examined PET and PLA polymer bottle ingredients based on toxicity, and included a preliminary exposure assessment of chemicals found to migrate from the bottles into the water.

A total of seven different groups of manufacturers and material types were tested in this study: three different never-filled PLA bottle types from two manufacturers, three different PET never-filled bottle types from three manufacturers, and one commercially-filled PET bottle type. Bottles from these seven groups were tested for different storage times (overnight, 3 months, 6 months) and storage temperatures (room temperature, 35 °C, 50 °C).

Bottles for the experiment were cleaned and filled with warm carbon-filtered tap water. The commercially filled water bottles were used as-is for the experiment. All water bottles were placed in the different temperature environments and the water from each was sampled at the end of the predetermined storage period.

Because bottle manufacturers use various proprietary formulations, full characterization of the chemicals in a material can be difficult. In order to develop a target list of compounds to track in the study, the researchers performed a literature review and conducted screening experiments to identify chemicals that could potentially migrate from the bottle matrix into water.

The screening protocol included direct thermal extraction combined with gas chromatography and mass spectrometry (GC/MS) to identify chemicals in the plastic bottle matrix. In this technique the materials were cut into small pieces and heated until they volatilized into a gas. The volatilized chemicals were taken directly to the GC/MS equipment for analysis.

To identify compounds that potentially could migrate into water, the plastics were exposed to pressurized hot water extraction and an Accelerated Solvent Extraction System (ASE) to simulate the most extreme leaching conditions for the water bottle. A final screening experiment was performed at the end of the study using stir-bar sorptive extractions (SBSE) directly from the test water bottles to complete the target compound list and confirm the presence of compounds found during the storage trials.

The team used three sampling techniques to identify compounds and elements present in the stored water at different temperature regimes. The GC/MS method was used to measure volatile and semi-volatile organic compounds, liquid chromatography-mass spectroscopy (LC/MS) was used for high molecular weight chemicals, and inductively coupled plasma mass spectroscopy (ICP/MS) identified chemical elements present in the water.

^{§§§§} The Environmental Working Group tested bottled water in 2008, followed by Congressional hearings and a U.S. Government Accountability Office report on the topic in 2009.

What's in the water?

The bottom line? None of the chemicals found in either PET or PLA bottles pose an immediate concern for public health as they were measured in the water during the storage and temperature conditions tested.

A total of twenty-nine organic compounds and twenty-four chemical elements were identified and measured in the storage trials for the PET and PLA bottles. Most of the organic compounds had average concentrations less than 0.1 parts per billion (ppb) and only seven rose above this value when stored for 6 months at 35°C. The concentrations of all compounds ranged from less than .001 ppb to approximately 1 ppb during this test.

Many of the elements present in the sampled water had high concentrations, but this was expected as they are minerals commonly found in drinking water. These include sodium, magnesium, silica, potassium, calcium, and iron.

Trends for the concentrations of the prioritized compounds were monitored during the experiment for the different storage and temperature regimes. A distinct trend was determined for increased concentrations of compounds in both the PET and PLA bottles for higher temperatures and longer storage times. Specifically, compounds in PET bottles on average increased by a factor of 9.4 for every 10°C increase in temperature over a 6-month storage period. Correspondingly, compounds in PLA bottles on average increased by a factor of 7.2 under the same conditions.

A more muted trend in increasing compound concentrations was found for longer storage periods – compounds in PET bottles on average increased by a factor of 3.8 for every three months and PLA increased by a factor of 3.7 over the same period. Concentrations of elements in the bottled water generally increased for both storage time and higher temperatures, but these results were mixed and less distinct than the trends found for the compounds.

Nine organic compounds and four elements identified in the storage trials were prioritized for a health hazard assessment. This prioritization was based on the known or expected toxicity of the chemical, the detection in significant quantities (greater than 1 ppb) during one or more of the trial conditions, and the connection of the chemicals to plastic production.

The nine organic compounds detected in the storage tests were grouped into three categories: phthalates, alkylphenol derivatives, and other aromatic compounds. Three phthalates from the list were flagged since they are known to impact mammalian endocrine systems. Three alkylphenol derivatives found in the storage water that are used as antioxidants in plastic packaging were prioritized due to their ability to act as an oxidant in biological systems or combine with proteins and cause toxic effects. Finally, three other aromatic compounds were listed because of their potential to chemically alter large biological molecules and membranes.

Four metallic elements were prioritized for a health assessment. These include antimony, tin, lead, and arsenic. Residual amounts of catalyst used in the manufacture of PET (antimony) and PLA (tin) are the most likely source of these metals found in the drinking water.

Arsenic, lead, and two phthalates were not detected in most samples and occurred inconsistently in the water. This indicated these substances were most likely not leaching from the plastic, but came from a different source. For this reason, they were not included in the exposure assessment portion of the study.

The final list of prioritized chemicals included seven compounds (diisobutylphthalate, benzophenone, phenanthrene, 2,2-dimethoxy-1,2-diphenylethanone, 3,5-di-tert-butyl-4-hydroxybenzaldehyde, 3,5-di-tert-butylbenzoquinone, and 2,4-di-tert-butylphenol) and two elements (antimony and tin). Most of these prioritized chemicals showed increased concentrations for both higher temperatures and longer storage times. For instance, antimony did increase over time in water stored in the never-filled PET bottles, but was the trend in the commercially filled PET bottles was not as pronounced.

The exposure assessment included the calculation of the concentration of each prioritized chemical under typical storage (3 months) and temperature (35 °C) conditions. From these values, the estimated human exposure of the prioritized chemicals was determined for children and adults using the mean and 95th percentile daily water intake rates. Results for the human exposure concentrations are listed for the prioritized chemicals found in both PET and PLA bottles.

It is important to note that some of the chemicals on the prioritized list, specifically benzophenone (a known carcinogen) and diisobutylphthalate (a known endocrine disruptor), are known to be a health hazard at certain levels. Despite the fact that no standard limits have been established for these chemicals in water, the preliminary health assessment of the prioritized chemicals found that the concentrations were too low to pose a significant risk to human health.

CSU Chico analyzes bioplastics degradation in ocean water

Part of the genesis for new materials like bioplastics is growing concern over the presence of durable and persistent plastic debris off the CA coastline and accumulating in our marine ecosystem. The realities and complexity of the marine debris dilemma are discussed in more detail at the end of Part 2. This section examines research on the rate of bioplastics breaking down in a simulated marine environment and the possibility of chemicals or byproducts that might be produced or released during the degradation process and then emitted into the water.

Following voluntary standards and test methods for plastic degradation in a marine environment (ASTM D7081-05 and ASTM D 6691), a research team at California State University, Chico, tested several bioplastic materials in ocean water attained off the Pacific Coast. As required, the testing was conducted in a controlled lab setting at 30 +/- 2°C (86°F) and the threshold of meeting 30 percent carbon conversion over a 6-month period was measured.

The research showed that PHA samples, Mirel films produced by Metabolix, exceeded the 30 percent carbon conversion rate (reaching 38-45 percent) while PLA, made by NatureWorks, demonstrated very limited amount of degradation (less than five percent) over the six-month period. Testing resumed for another 6 months, and after a full year Mirel film showed 51-81 percent biodegradation, while the PLA bag and bottle samples tested less than 10 percent biodegradation. It's important to note that PLA is typically designed to be compostable in a commercial compost environment; thus, the results for this material type are not that surprising. As with other aspects of this research project, Stanford's PHB was not yet produced in sufficient supply for testing. Therefore, Stanford PHB testing was not included in the CSU Chico research.

Whether this means PHA can disappear in the ocean in about a year is not clear. Although the rate of degradation for the PHB materials was fairly high, test conditions in the standard are not representative of Pacific Ocean temperatures, which average 13-18°C (55-65°F). In addition, conditions required to initiate the degradation process do not exist in deep ocean waters. Finally, the PHA was film – which is thinner than a bottle wall. Researchers observed full PLA and PHA

bottles over one year in a simulated marine environment and found that the PHA container demonstrated some amount of degradation in its wall, but it was not significant.

Moving beyond the physical breakdown of the bioplastics, another question concerns toxicity testing. Though comprehensive toxicity tests of marine organisms were not conducted, the researchers employed several testing methods at the molecular level to search for chemicals in the water. They used Fourier Transform Infrared Spectroscopy, Attenuated Total Reflectance, and Differential Scanning Calorimetry to evaluate the presence of toxic chemicals or byproducts that could potentially occur as a result of the degradation process. None were found. If there had been any indication of the presence of chemicals, the contractor was prepared to utilize Gas chromatography mass spectrometry for further analysis.

PART II –

Bioplastics’ End of Life and the California Recovery System

Collecting, Sorting, and Processing Bioplastics

Part I examined the production of bioplastics and the many ways this new class of products and packaging touches California. Materials acquisition and manufacturing represent the front end of a product’s life. This section discusses what happens in the later stages, when consumers finish with a product.

California’s recovery programs evolved over many years with significant public and private investments. Can the infrastructure already in place be preserved, but still accommodate the influx of new materials entering the California market? How can California best manage the end of life for products and packaging? To increase understanding of these issues, CalRecycle funded several studies exploring bioplastics’ place in our present recovery system and some environmental implications of their use.

Setting the scene: California’s recycling and compost programs

California has a long history of waste prevention and recovery programs. The 1980s ushered in a new era for dealing with the state’s discards, beginning with the beverage container recycling program (Margolin, Assembly Bill 2020, Chapter 1290, Statutes of 1986) and the landmark Integrated Waste Management Act (Sher, Assembly Bill 939, Chapter 1095, Statutes of 1989), which instituted the “Reduce, Reuse, Recycle” approach now familiar to any schoolchild.

Bottles and cans at the forefront of packaging recovery

The beverage container law dramatically shifted the recycling of plastic packaging in our state from a minor community activity to a major link in the industrial supply chain. It sets a deposit or

“California Refund Value” (CRV) on every beverage sold in the state, currently five cents for containers under 24 ounces and 10 cents for larger bottles or cans. A network of Convenience Zones around major supermarkets provides statewide access to recyclers, who receive empties and pay refunds to consumers. Local government curbside recycling programs also receive payments based on the proportion of all CRV containers they collect. The State controls unredeemed deposits, providing funding for recycling incentives, grants and other programs.

With the public and private infrastructure investments jump-started by the bottle bill, the CRV recycling rate has mushroomed since the program’s inception. Californians recycled more than 17 billion beverage containers in 2012 for an 82 percent recycling rate,⁷⁷ significantly boosting materials available to the U.S. scrap market. Moreover, the program set in motion substantial changes to the price and demand for recycled plastic, helping to launch plastics recovery as a viable industry in the state. Within a decade or two of the program’s inception the PET industry had “evolved ... to the point that PET recycling is now established and recycled PET is an accepted global commodity.”⁷⁸

Perhaps the most contentious element in California’s approach to beverage containers has been the Processing Fee (PF). Beverage companies pay a fee to CalRecycle based on the difference between the scrap value of each material and the actual cost to recycle that material. CalRecycle then distributes the fee proceeds to processors, who, in turn, pass them on to recyclers. The idea is to help support the recycling industry when the actual cost of processing containers exceeds the value of the materials sold. In theory, the fees create an economic incentive for manufacturers to package their products in more easily recycled materials.

PFs remain a central feature in California’s system for recovering bottles and cans, with important implications for bioplastic packaging. The PFs for plastic bottles are based on statewide surveys of scrap value and recycler costs and assessed according to the resin code on the bottle. So widely recycled PET (resin code #1), for example, carried a low PF in 2013 (\$0.00008 per container sold). But the PF for the category that includes PLA or PHB bottles (resin code #7 - “Other”) came in literally a thousand times higher, about 8 cents a bottle.

Diversion and AB 939: Waste is a resource out of place

Three years after California began implementation of the beverage container recycling program, lawmakers substantially revised the state’s waste management policies. In one of the most ambitious “rates and dates” laws of that era, AB 939 mandated each city and county to divert 50 percent of its waste from landfills by 2000. It emphasized an *integrated* approach, institutionalizing the now-familiar hierarchy of reducing waste at its source, reusing products and materials when possible, recycling materials that cannot be reused, and landfilling or otherwise disposing as a last resort.

In more than two decades since the law’s inception, California experienced a proliferation of curbside recycling programs and a network of MRFs for sorting and processing the recyclables collected. Private companies operate most of these programs along with facilities that process construction and demolition debris, metals, paper, glass and of course, plastic. All told, the state has more than 650 such “intermediate processing facilities” in CalRecycle’s database.⁷⁹

Moreover, entrepreneurs and local governments have developed a separate system for handling organic waste, which comprises more than a third of the solid waste in most communities. The CalRecycle database lists 369 organic material processing facilities including commercial

composters and other facilities that manage organic materials like yard waste, food scraps, wood and agricultural byproducts.⁸⁰ Composting regulations address permitting, feedstocks, odor control, product quality, and public health.

Accurate measurement has been essential for this paradigm shift. Gathering the necessary data to track progress in a state as large and diverse as California is challenging, to say the least. The current standard for charting our progress in meeting the mandates of AB 939 is *per-capita disposal reduction* – the average amount each person throws away compared to historical trends. The baseline is the average per-capita solid waste generation from 2003 to 2006. By this yardstick, Californians achieved a “diversion rate equivalent” of 65 percent in 2010.⁸¹

Focus on plastics

One program deserves special mention in the discussion of packaging and bioplastics. Enacted in 1991, the Rigid Plastic Packaging Container (RPPC) law (SB 235, Hart, Statutes of 1991, Chapter 769) targeted many common rigid containers. They are defined as those sold or offered for sale in California that are made entirely of plastic (except for incidental portions of the packaging); have a relatively inflexible shape or form; have a capacity of at least eight ounces and not more than five gallons; and are capable of at least one closure. Packaging for food, beverages some other products are exempt.

The RPPC program generally requires brand owners and other product manufacturers to meet one of several options, including 1) reducing the amount of plastic in their packaging by 10 percent, 2) providing for reuse or refilling of the container, 3) achieving at least a 45 percent recycling rate for a specific class of RPPC, or 4) manufacturing the RPPC with at least 25 percent postconsumer recycled plastic. Manufacturers of products packaged in RPPCs must register with CalRecycle and may be called upon to certify compliance. Using postconsumer feedstock has been the most common compliance method among affected producers, historically accounting for more than half of compliant containers.⁸²

New regulations in 2013 clarified the RPPC definition to include such common items as heat-sealed clamshell packaging and buckets with metal handles, among other changes. The new rules also clarify that “resin-switching” – substituting a different resin type for one previously used to manufacture the same container – is not a valid compliance option. CalRecycle estimated the 2013 regulatory changes would bring roughly 100 million pounds of additional containers under the RPPC umbrella annually.⁸³

Where do bioplastics fit in?

The vast California recycling system outlined above represents both an opportunity and a challenge for certain bioplastics. Many analysts predict strong growth in bioplastic packaging. One study pegs rigid packaging – including clamshells and other types covered by our RPPC law – at about half of all packaging made from bioplastic.⁸⁴ As this sector gathers steam, the RPPC toolbox may become one more policy driver to accelerate end-of-life options for bioplastics. At the same time, the very success of PET recycling is in one sense an impediment to the recovery of PLA: since the market share of PLA packaging has been miniscule compared to PET, there has been little incentive for recyclers and reclaimers to invest in new technologies that might make PLA recovery viable.

Yet the California system eventually could integrate new materials like bioplastics with mainstream recovered commodities. Collection programs are mature and reclamation technologies have become more sophisticated. Bioplastics potentially could benefit from certain program payments at some point in the future, as they gain a foothold in the packaging universe. Perhaps the right mix of economic incentives, technology and market influences will permit conventional plastics and their bio- counterparts to coexist. (The Coca-Cola PlantBottle, biobased but recyclable with traditional PET, is an example addressed later in this report.)

What's past is prologue: the 75 percent imperative

AB 939, the bottle bill and their related programs heralded a sea change in the management of California's waste during, bringing the state to the forefront of resource management in many ways. But now Californians are once again rethinking approaches to reduce the environmental impact of materials. Old notions of landfill diversion are giving way to broader conceptions of "materials management" and "sustainability." This report will not attempt to pin down those overused terms, but the general idea is to account for environmental impacts across sectors so that not only the present but future generations can thrive.

The concept underlies California's sweeping new materials management law, the heir to AB 939: Assembly Bill 341 (Chesbro, Chapter 476, Statutes of 2011), which sets an ambitious statewide goal of source-reducing, recycling or composting at least 75 percent of our solid waste by 2020. AB 341 does not do away with the local diversion mandates of AB 939, but instead offers a chance to move forward with a more straightforward definition of recycling to measure statewide progress when setting a baseline, establishing targets and measuring success. This change encourages increased use of spent materials as resources to make new products.

One thing is clear, regardless of the policy path ahead: to achieve this goal, California will need to develop a great deal more capacity for handling recovered materials, from recycling collection and composting to remanufacturing. Under a business-as-usual, medium-growth scenario, disposal-related activities would grow to 43 million tons in 2020; achieving 75 percent recycling using stricter definitions of recycling will require re-directing more than half of this amount (22 million tons).⁸⁵ This will require bringing many more recovery facilities online in the next decade, along with advanced recovery technologies and capabilities.

More facilities will need to expand their customer base as well. In the past decade, China and other countries have absorbed a great deal of the output from California plastics recyclers. As recently as 2008, 58% of the PET collected in the U.S. was exported, much of it from California and the West Coast.⁸⁶ But the export market is uncertain. Plastic exports dropped during the recent recession. More to the point, China erected a "Green Fence" in the fall of 2012, a new policy to crack down on contaminated scrap imports entering the country. U.S. exporters of mixed-resin bales, in particular, suddenly found a reliable market pulled out from under them.

Navigating uncertain seas

Reaching California's 75 percent target undoubtedly will require going beyond the "low-hanging fruit" to capture not just more materials, but more *kinds* of material as well – bringing us full circle to bioplastics as a harbinger of the new products and packaging formulations inevitably entering the marketplace.

One example is polyethylene furanoate (PEF). This new member of the polyester family reportedly has superior properties to its cousin PET. And unlike PET on the market today, PEF packaging can be produced entirely from biobased feedstocks like corn, sugar cane or agricultural waste. Coca-Cola, Danone and Alpla – some of the world’s largest food industry companies – have already inked multi-million dollar agreements with PEF producer Avantium to bring PEF to market by 2016. Avantium is constructing a 50,000-ton per year plant to meet this timetable.⁸⁷

With this level of commitment to a new material, the impact on packaging – and options for end-of-life disposition in California – could be substantial. Is PEF recyclable? Avantium says it is. Can PEF bottles be recycled with their PET counterparts? Avantium states, “Experiments to determine the compatibility of PEF with PET recycling show PEF has no impact on mechanical and physical properties of PET.”⁸⁸ Whether PEF will have “no impact” on commercial-scale recovery operations remains to be seen. Factors like market penetration, sorting technologies, end-use specifications and, of course, public policy will need to be considered.

The contamination conundrum

In any case, bioplastics and other new materials are gaining traction in the marketplace. New materials present both opportunities and challenges for novel ways to harness the ever-expanding materials management universe.

The concept of contamination is important in this discussion. Clean materials are at the heart of any recovery operation, essential for recyclers and composters to stay in business. Too much dirt, too many incompatible materials, too much of anything different, and the desired postconsumer material loses value or even becomes unusable for manufacturing. Even perfectly recyclable resins in the wrong bin contribute to the problem.

But recycling is also a volume game. Manufacturers rely on a consistent supply of feedstock and steady pricing to produce finished products, which can put the recovery industry at a disadvantage compared to its virgin materials counterpart. A key strategy to overcome this challenge is high-volume collection and the economy of scale it offers; higher volume can mean lower costs per unit of output. One reason so many communities have adopted single-stream collection (placing all recyclables in a single bin) is the opportunity it offers for dramatically increasing the volume of captured recyclables.

The problem arises when these two forces – the need for clean materials and the need for more of them – collide with each other. While single-stream has significantly augmented the amount of recyclables collected at the curb, it also boosted contamination over the last couple of decades as California communities converted to the method. Debate still pervades the recycling industry over the costs and benefits of the single-stream approach.

Steps along the way

The path of PET containers through the recovery system illustrates the contamination challenge. Figure 5 below depicts a typical pathway for a plastic bottle moving through the stages of recycling, described in the narrative below.

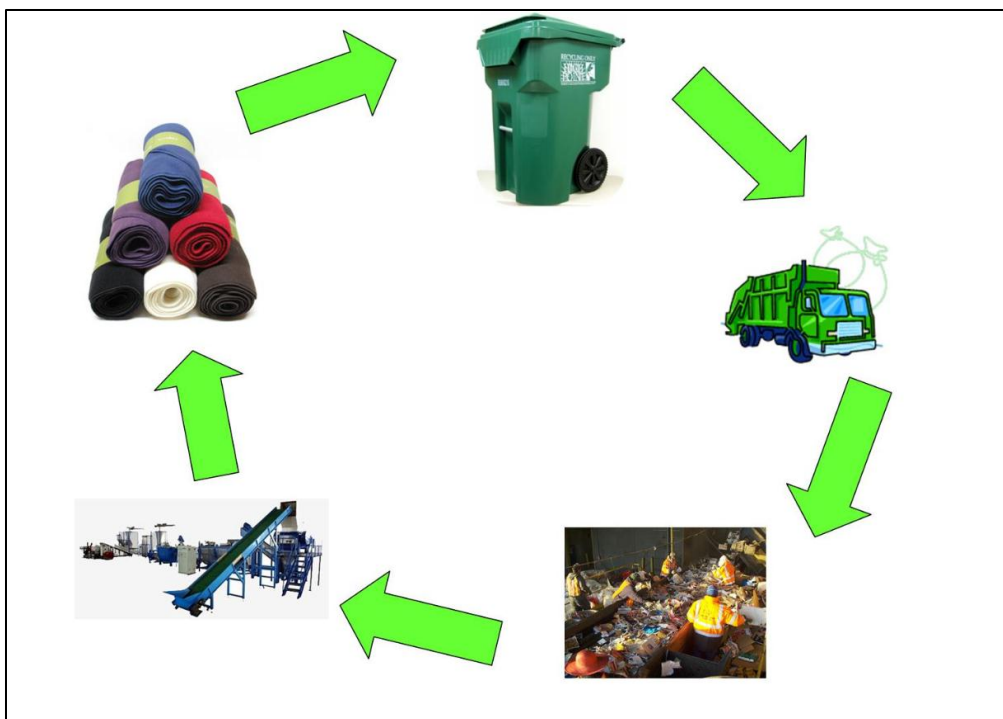


Figure 5 - Typical stages in plastic recycling

It starts with collection, for example when a consumer sets out his recyclables at curbside. *****
 Right away contamination rears its head: Did Mr. Jones use a plastic bottle as a convenient receptacle for his cigarettes at the party the night before? Did he leave peanut butter in the bottom of that jar he threw out? Did he toss some garbage in with the cans and bottles in the bin under the sink?

Then the truck comes on collection day. A mechanical arm picks up the bin of mixed recyclables, dumps them in the back, and compacts the load to reduce the number trips to the recovery facility – and presents another chance for compromised material quality. Plastic can withstand the compaction pretty well, but glass is not so forgiving. Broken glass permeates the mix, along with the peanut butter and anything else that made its way into the bin. By its nature mixing recyclables opens the door for cross-contamination among recyclables and by foreign materials.

Next the load heads off to the place where everything will be sorted, the MRF. In the recovery industry, effective sorting is essential to the economics of the enterprise. Consequently, the industry has invested heavily on personnel and equipment to sort mixed materials. The modern MRF is a marvel of engineering, with conveyor belts, screens, trommels, magnets, eddy current

***** This is a general description of the process. In reality the recovery pathways are numerous, with some more prone to contamination than others. CRV containers redeemed at recycling centers, for example, generally are much cleaner than those captured at the curb, primarily because most are segregated from the start. Also, manufacturer specifications will determine the level of quality or additional processing required, with food-grade standards generally being the most demanding.

separators and air knives, all working together, along with human pickers, to produce clean materials at the back end for sale to paper mills, glass plants, plastic reclaimers and other industries.

MRFs have come a long way in recent years. The investments undoubtedly have increased efficiencies and allowed more recycled materials than ever before enter into commerce. And yet those PET containers that left Mr. Jones' house may not all make it into a bale on the back dock, waiting for shipment to the next link in the supply chain. The industry speaks of "yield loss" in processing, the difference in the volume of materials coming in versus what goes out. In any sorting venture a certain percentage of the desired commodity will be mis-sorted into bales of other materials (such as PET bottles baled with paper), mixed with foreign substances (peanut butter again) or simply missed altogether and sent out with the trash (residuals). The greater the yield loss, the lower the return on investment, everything else being equal.

Let's assume Mr. Jones' containers made it through the MRF into a PET bale. The MRF sells to a reclaimer for further processing, the last stage before recycled bottles can be turned into pellets for manufacturing something again. The typical reclaimer in California uses a "wash and grind" system to prepare the material for industrial feedstock. Bales from the MRF are broken apart, the bottles shredded, and the resultant flakes sent through a "sink-float" tank to wash the material and separate out other resins. Differences in density means HDPE floats and PET sinks, allowing for separation of each. The reclaimer may employ optical sorters or other methods to ensure quality control. The clean and dry flakes are fed into an extruder, which melts and forms them into pellets. Once again the goal is to keep contamination and yield loss to a minimum.

The final stage in the pathway to a recycled-content product is the end-use manufacturer, in this case the customer who purchases pellets from the reclaimer. Depending on the product or package being made, the facility may employ additional mechanisms to ensure material quality. Produce containers are a typical use for recycled PET in California, that pack of mixed baby greens brought home from the grocery store. Food-grade RPET must go through specialized equipment and meet FDA purity standards, which are not required for other product types. The recycled PET pellets, or RPET, first are extruded into a thin sheet. Impurities in the extruder can cause rejected product (yield loss again), so the machines employ fine-mesh screens to filter out small bits of metal and other contaminants. More impurities mean more screen changes and higher cost. Finally the sheet is thermoformed (molded under high temperature) into individual containers.

Every stage in the chain presents quality control challenges. Proper separation of dissimilar materials is essential; in the wrong place even highly desirable commodities like PET become contaminants. Poorly sorted recyclables lose value and may become the Achilles' heel to a company's bottom line.

A 2012 study by the Container Recycling Institute found the combined yield loss in a single-stream system can be high indeed – as much as 27 percent of material entering a MRF may be lost somewhere in the supply chain by the time it becomes feedstock clean enough to use in manufacturing.

The yield losses vary by material and a facility's place in the system, as well as by separation technology employed, geography and other factors. Regardless, in just the reclaiming segment California PET facilities reported in 2011 a 28.9 percent yield loss for CRV bottles processed at their facilities. Nationally similar facilities processing curbside material reported an average of 35

percent yield loss, according to the National Association for PET Container Resources (NAPCOR).

New materials in the mix

Where do bioplastics fit in on the contamination continuum? Like so many things, the answer is, “It depends.” Much depends on the physical composition and intended use of a given material. If a reclaimer is processing PET bottles into beverage-grade RPET pellets (perhaps the most demanding end-use), then even small variations in material composition can add up to large and costly impacts on purity. Contamination can come from chemically similar resins (PET-Glycol or PETG) as well as from biobased or biodegradable plastics (PLA).

But what constitutes an unacceptable level of contamination is not settled. Contamination is incremental, with each undesired element adding to the impact, some more potent than others. Determining a precise threshold for any given material is complex. Yet at some level, too many straws break the camel’s back.

It is important to understand contamination depends somewhat on the end objective. To a PET reclaimer, PLA is to be avoided even in small quantities. For one thing, PLA melts at much lower temperatures. Too much PLA mixed with PET reportedly can cause the recycled PET flake to degrade; one report suggests even at levels lower than one in a thousand (0.1 percent), PLA in the PET stream will produce RPET “too degraded for PET’s major applications.”⁸⁹ But the reverse may not be true. A PLA reclaiming operation (just one exists in North America at present) may be able to tolerate relatively high levels of other resins.⁹⁰

In any case, biodegradable bioplastics in general have raised a hue and cry from recyclers. Much of this has been a reaction to PLA, the market leader in many bioplastic applications. In addition to the aforementioned reclaiming issues, PLA packaging can be difficult to distinguish from its PET cousins, fooling even sophisticated optical sorters designed to separate resins. PET recyclers worry a material designed to disintegrate will weaken products made with RPET, undermining the very core of their business.⁹¹ If PLA makes it into PET bales, the two will be shredded together at the reclaiming facility. A similar relative density means the resins both would sink, confounding customary operations.

In 2009 NatureWorks, the primary producer of PLA in North America, and Primo Waters Corporation commissioned research to test the ability of near-infrared (NIR) optical sorters to pluck out PLA bottles from PET. That study found 93 percent of the “seeded” PLA bottles were correctly separated. NatureWorks’ white paper on the research suggested NIR sorters are a viable option for recycling operations, concluding “there is no technological barrier to recycling bottles made from plants instead of oil.”⁹²

NAPCOR was quick to respond. It released a strongly worded statement warning against adding PLA containers to the PET recycling stream and challenged the methodology used in the PLA study. The organization pointed out the high cost of NIR sorters, stating many recycling operations do not have such systems; those who do expect at least a 95percent separation rate.⁹³ The Association of Postconsumer Plastic Recyclers (APR) also chimed in, stating any level of PLA over 0.1 percent in a PET reclaiming facility would be considered unacceptable contamination.⁹⁴

A few years ago it seemed PLA water bottles were poised to make a big splash in the California market. CalRecycle began to hear reports of new beverage companies jumping in to use the material. However, NatureWorks, the primary producer of PLA in North America, has modified its Ingeo™ business plan in part because of the reaction by recyclers to PLA bottles. NatureWorks has stated the company is moving away from the beverage bottle market for now, instead “selling Ingeo grades into consumer products where the potential for recycle stream contamination is minimal” – in other words, focusing on market sectors unlikely to disrupt an existing recycling infrastructure. This, the company suggests, will allow it to help develop end-of-life systems while “achieving scale safely” as its PLA sales grow.⁹⁵

Contamination, part two: composting

Recyclers are not the only ones concerned about bioplastics in the existing scheme of things. The compost industry sees potential problems in at least four areas: sorting, compostability standards, organic certification and bioaccumulation.

Sorting and standards

As in the recycling industry, effective separation of materials is paramount for producing a quality compost product. California is home to about 100 industrial composters that process green waste (yard trimmings, etc.), food waste or other organic materials diverted from landfills.⁹⁶ Most of these produce a nutrient-rich soil amendment for sale to agricultural and other customers.^{††††} Plastics traditionally are contaminants in the organics processing system, as they do not decompose rapidly – the essence of industrial composting – and lower the quality of the end product.

But what about biodegradable plastics? Aren’t they designed for composting? Perhaps. Truly compostable materials, plastics included, must meet strict specifications as industrial feedstock. As discussed in Part I, the ASTM plastic compostability specification D6400 requires thresholds for disintegration, biodegradation and ecotoxicity. The ASTM standard itself has been under review in recent years to more accurately reflect real-world composting conditions. For instance, the 2012 update to D6400 now requires 90 percent of the organic carbon in feedstock to be converted to carbon dioxide within 180 days, up from the less-stringent requirement of 60 percent conversion.⁹⁷ Further modifications have been made recently or are under consideration for related standards and test methods, such as updated methods for measuring disintegration.^{****} As of this writing, CalRecycle has supported the proposed changes as more accurately reflecting the needs of the state’s compost industry, as long as certain standards for toxicity testing, etc. are maintained.

Even if a plastic product is certified compostable by an independent third party like the Biodegradable Products Institute (BPI), many composters are wary simply because it can be difficult to distinguish between compostable and non-compostable items. In reality many, if not

^{††††} Precise numbers of facilities are difficult to determine due to differences in feedstocks accepted, operating practices and end markets.

^{****} See, for example, ASTM D6954-04(2013), *Standard Guide for Exposing and Testing Plastics that Degrade in the Environment by a Combination of Oxidation and Biodegradation*.

most, industrial facilities screen out all plastics, either before the composting process or as a quality control measure on the back end. Furthermore, many facilities must process their materials faster than the six-month window specified in D6400. A 2010 survey of U.S. composters by the Sustainable Packaging Coalition (SPC) revealed nearly half of respondents actively compost their material for 70 days or less.⁹⁸

The SPC also found 43 percent of respondents reported changing their equipment or operations to address compostable packaging, including

- Longer curing times;
- Pre-sorting feedstock containing packaging into separate windrows;
- Adding a grinding, mixing and/or screening stage;
- Creating bigger piles, turned less often (for increasing heat and moisture); and
- Increased labor for litter control.⁹⁹

Despite efforts to adjust composting practices, adequate separation of bioplastic materials remains a challenge for most operations. As with recycling, the more fundamental task is to sort out *any* incompatible material. A 2012 study in Portland, Oregon of composting “overs” (the materials screened out and discarded) found “the overwhelming majority of the plastics in the overs were nondegradable plastics. As such, limiting the distribution and promotion of truly compostable items will do little to reduce the total plastic in the overs stream.”¹⁰⁰

As more food composting programs gear up in California, the sorting problem becomes more acute, since cups, flatware and other food-related items often end up in the organics bin. A 2008 survey identified 16 food composting programs in our state.¹⁰¹ CalRecycle estimates there are now 26 compost facilities accepting food materials as of this writing.

Food waste collection programs are expected to increase significantly. They are part of a strategy to “Move Organics Out of the Landfill,” one of six critical focus areas CalRecycle has identified to achieve 75 percent recycling.¹⁰² Compostable organics comprise about a third of the waste landfilled each year, and food scraps make up perhaps half of that total – about 5 million tons per year.¹⁰³ Concurrently, the U.S. EPA and the U.S. Department of Agriculture (USDA) have partnered to roll out the “US Food Waste Challenge,” designed to encourage companies and institutions “across the food chain” to reduce, recover and recycle food waste and to measure their efforts.¹⁰⁴ While non-degradable plastic food serviceware hinders these efforts, truly compostable plastics could play an important role in capturing additional food tonnage, since consumers would be able to toss both their leftover scraps and the implements used to eat them into the organics stream.

Keeping it organic

Another wrinkle in the bioplastics-and-composting puzzle is organic certification. The USDA oversees the National Organic Program (NOP), which ensures food or agricultural products labeled “organic” will meet legal and industry standards for items grown without synthetic fertilizers, genetic engineering and so on. The term “synthetic” is important here. Many synthetic substances are prohibited under NOP regulations, but whether certain bioplastics fall into that category is a murky issue. The regulations define the term as

“A substance that is formulated or manufactured by a chemical process or by a process that chemically changes a substance extracted from naturally occurring plant, animal, or mineral sources, except that such term shall not apply to substances created by naturally occurring biological processes.”¹⁰⁵

Under this definition, should bioplastics generally be in or out as an input to organic compost? The answer is not clear. Even substances that occur naturally may be prohibited if produced by artificial means. For instance, lactic acid, a building block of PLA, is prohibited under the NOP if it is manufactured using recombinant DNA technology.¹⁰⁶ After considerable discussion by the National Organic Standards Board (NOSB), an advisory body, the USDA determined compostable plastic products must be addressed on a case-by-case basis.¹⁰⁷

The implications are significant for producers of organic compost. A U.S. Composting Council (USCC) primer on compostable plastics explained the scenario: “If the NOP decides these [bioplastic production] processes disqualify bioplastics as a feedstock for organic certified compost, commercial composters who produce organically certified material will need to either invent a means to economically remove bioplastics from feedstock, or refuse any source of material that includes bioplastics.”¹⁰⁸ Either way, the market impact could be considerable, especially in California with its many organic farms that purchase compost.

As it stands, certifiers of organic products like the Organic Materials Review Institute (OMRI) include bioplastics under the “prohibited synthetics” umbrella unless a specific product has been exempted by the USDA. Even so, the founding President of OMRI, now a private consultant, has urged a cautious approach to the gray areas surrounding the issue. He notes, “We accept manure that contains antibiotics, we accept food waste that includes synthetics as part of the food chain, so we need to look at the overall context... There may be a number of social benefits to organics from some of these [bioplastic] materials, and we should look carefully in order to make a balanced decision.”¹⁰⁹

As of October 2013, the NOP’s National List of Allowed and Prohibited Substances did not contain any bioplastic product classified as an “allowed substance.”¹¹⁰ However, the NOSB has recommended allowing “biodegradable biobased mulch films” (agricultural films enhancing crop production and designed to biodegrade between growing seasons) if they meet strict specifications. The USDA published a proposed rule for these products in August, 2013.¹¹¹ While not likely to become inputs to organic compost, in theory their approval could point the way for other bioplastic products.

The California Department of Food and Agriculture (CDFA) enforces the California Organic Products Act of 2003 (Strom-Martin, Chapter 533, Statutes of 2002), which essentially adopted the NOP list. Sellers of organic products must register with the CDFA or the California Department of Public Health. Composting operations must be licensed and “organic input materials” must be registered and inspected, a result of increased scrutiny after a fertilizer manufacturer was found to have sold organic products “adulterated with a synthetic ingredient.”¹¹²

Breaking down and building up

Closely related to the organic certification challenge is the concept of bioaccumulation. The term is used in a variety of contexts, but the U.S. EPA has defined it as a “general term describing a process by which chemicals are taken up by an organism either directly from exposure to a

contaminated medium or by consumption of food containing the chemical.”¹¹³ Could such an effect occur in fields using compost made with bioplastics in the feedstock? Composters have been concerned potentially toxic ingredients, additives or byproducts from bioplastics could be released during composting and accumulate in the environment over time.

Bioaccumulation is normally a beneficial process essential to the health of an organism, like the daily accumulation of vitamins and minerals needed for survival. However, certain substances can build up and eventually overwhelm the organism, resulting in disease or even death. Whether bioaccumulation is helpful or harmful depends on a host of factors, including the concentration of chemicals, whether they are fat- or water-soluble, the duration of exposure, and the ability of an organism to break down and eliminate a given chemical from the body.¹¹⁴ The extent of bioaccumulation can vary between species and even among individuals – a “large, fat, long-lived” organism would generally bioaccumulate more than its small, thin and short-lived counterpart. “Thus, an old lake trout may bioaccumulate much more than a young bluegill in the same lake.”¹¹⁵

Adding to the difficulty of determining bioaccumulation potential of a given plastic is the role of additives in finished products. As previously discussed, plastic product manufacturers may use a variety of additives to improve the performance or processability of a resin. So even if tests for a base resin indicate the plastic will not bioaccumulate harmfully, an actual product fashioned from the resin and *other ingredients* added to the formula may have a different profile.

Perhaps the most prominent example illustrating concern over bioaccumulation is Bisphenol-A (BPA), an ingredient in certain plastic bottles and other products.¹¹⁶ Some studies suggest very low doses of this so-called “endocrine-disrupting” compound can seriously affect human health¹¹⁷; other toxicologists do not believe there is clear evidence of this.¹¹⁸ Regardless, the notion that very small amounts of some chemicals can lead to cumulative health effects turns on its head a basic premise of toxicology that “The dose makes the poison.” The debate over BPA may explain some of the concerns about degradable bioplastics releasing harmful chemicals that will bioaccumulate.

So the process of bioaccumulation can be complex and difficult to measure. Isolating the effects of specific constituents in compost is challenging, and research on the bioaccumulation potential of bioplastics in compost has been scarce. A 2009 fact sheet on compostable plastics by the California Integrated Waste Management Board (which later merged into CalRecycle) noted

“...the CIWMB is not aware at this point of any information or research that demonstrates whether or not bioaccumulation of any toxic substances occurs from compostable plastics. The bioplastic industry is working to provide research that assesses whether or not chemicals from compostable plastic products accumulate and transfer through the food chain as a result of land application of compost that has these products as feedstock.”¹¹⁹

It appears research on the bioaccumulation potential of bioplastics in compost remains meager. BPI did sponsor some unpublished tests and provided information about them to CalRecycle. Those tests found no evidence of bioaccumulation from base resins, but products with additives were not addressed. A literature search by CalRecycle staff turned up no publically available studies on the topic since the 2009 fact sheet.

Note concerns about the bioaccumulation potential of bioplastics don't stop at soil: some fear plastics in general may release harmful constituents into our waterways and oceans, to be taken up by marine organisms and birds. We discuss marine debris and bioplastic bioaccumulation possibilities in an upcoming section ("Environmental Profiles of Plastic Packaging").

On the frontier: new materials, new technology, new approaches

Californians have made great strides in the way we manage materials. Our state has robust systems for recycling and composting products and packaging when they finish their useful lives. Yet as we have seen, the introduction of new materials like bioplastics can have unintended consequences. Undoubtedly there are some who would like to see these new materials simply fade away.

But that scenario seems unlikely. Bioplastics as a class are diverse and have entered many markets already, though inevitably some products will fall by the wayside. The market drivers discussed at the beginning of this report – ocean pollution, climate change, green chemistry, oil dependence – have generally favored these types of products.

If biobased and biodegradable polymers are not going away, then a key question is whether and how these new materials can be integrated into our recovery systems without negative consequences. Possible answers to that question are under investigation on a number of fronts, though much remains unsettled. The sections below present a sampling of these efforts, grouped into Technologies, Materials and Approaches (recognizing these categories overlap).

Technological advances

The previous discussion of contamination makes one thing abundantly clear: effective separation of materials is key to successful recovery. The burgeoning single-stream collection industry has given rise to ever-more sophisticated equipment for sorting through the pile. In particular, engineers have developed optical sorting systems to separate commingled recyclables from each other. More and more MRFs (at least the large ones) are deploying such machines, often investing hundreds of thousands of dollars.

Optical sorting machines employ a variety of technologies to exploit physical and chemical differences between materials. But in general optical systems consist of conveyors and infeed hoppers, cameras to detect materials passing in front of them, a computer to analyze the camera's signals, and precisely-timed air jets to direct materials into different bins. Cameras may "read" visible light, x-rays, near-infrared or other wavelengths. Several companies have developed sorters to separate polymers from each other, either as whole containers or after plastics have been shredded.

The effectiveness of optical sorters has been difficult to ascertain. Results can be affected by many factors, including the condition of incoming materials, technology employed, processing speed and operator expertise. While many vendors attest to the accuracy of their machines, impartial data have been hard to come by. Mindful of this state of affairs, CalRecycle's Division of Recycling awarded a grant to build and test an optical system for sorting bioplastics under real-world conditions, and to gather stakeholder input on the sorting trials. The grantee Future 500 is a non-profit consultancy based in San Francisco, with a mission of engaging corporations and their stakeholders with market-based solutions to social and environmental challenges.

The Future 500 Bioplastics Sorting Project

The Bioplastics Sorting Project tested removal of bioplastics from several waste streams and facilities around California. The project team also analyzed discarded plastics lost to landfills statewide and convened a stakeholder forum to discuss the data and potential policy implications. At inception the project focused on separating PLA bottles from PET containers, but later added trials on other bioplastic packaging (clamshells and cups), and tested the system's ability to sort multiple plastics from each other. Future 500 evaluated the effectiveness of the sorting technology, but the project scope did not include the economic factors or costs associated with using the system at a MRF or reclaiming facility.

The project team discussed a number of approaches for conducting the sorting trials, in the end settling on constructing a mobile system that could test materials at several MRFs and reclaimers. Through a Request for Proposal, Future 500 awarded a contract to Pellenc Selective Technologies, a vendor of sorting systems based in France. Pellenc, in turn, hired Titus Maintenance of Fontana, California to construct and operate the system, building in Pellenc's *Mistral M12-15T* optical scanner. *Figure* shows the mobile system in operation at a MRF, including the infeed hopper, incline conveyor, air classifier and Pellenc scanner module (light blue box at the end).



Figure 6 – Future 500 mobile sort system in operation

The Pellenc scanner analyzes each container on the conveyor belt for shape and chemical composition. It can be calibrated to sort different fractions depending on the desired outcome, separating the incoming material three ways (such as PET, PLA and all other materials) or two ways (such as PLA and all other materials). The scan triggers air jets in fractions of a second, which push containers up or down (the “positive” sorts). The remaining fraction is achieved by allowing a container to continue along the conveyor unimpeded (a “negative” sort). *Figure 7* depicts the flow of containers as they are sorted by the optical unit.

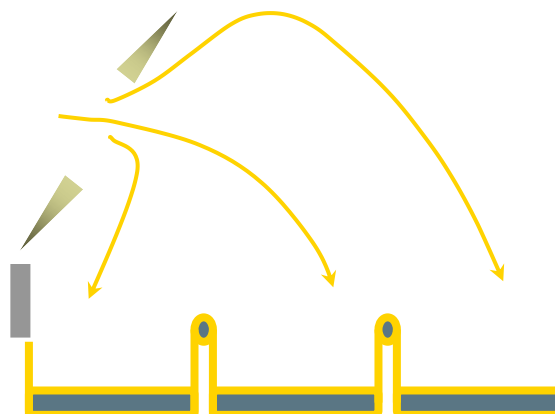


Figure 7 – Separation of incoming material into three fractions

The team tested the equipment on samples from five types of material streams, gathered from eight California MRFs and three reclaimers over several months in 2011 and 2012. It posed four main research questions:

- Can the optical sorting system effectively separate PLA bottles from PET bottles, so that clean PET would continue to be available to PET reclaimers?
- Can the optical sorting system effectively separate PLA from other materials, so that PLA products could be recovered for recycling?
- Can the optical sorting system effectively separate other (non-bottle) PLA products, especially cups and food service items, from a mixed plastics stream?
- Can the optical sorting system effectively separate various other types of plastics from each other, from a pre-sorted mixed plastics stream?

The original intent of the mobile model was to bring the system on site at each facility. However, this became infeasible due to space constraints, transportation expenses and the necessity of mounting some of the pre-processing equipment on a separate truck. The research team conducted later trials at the Titus facility in southern California, trucking in samples from MRF operators and reclaimers in the region. They collected samples from the following material streams, as described by the contractor:

Sorted PET. PET bottles that had been positively sorted from a MRF container line (i.e. separated from other materials by hand and/or machine into a dedicated PET bin). This stream was fed into the mobile system and processed by the optical technology to remove

non-PET materials, especially PLA, that inadvertently had been separated into the PET bin by the MRF.

Sorted HDPE. HDPE containers positively sorted from a MRF container line. These were run through the optical sorting machinery to recover PLA and PET bottles that inadvertently had been sorted as HDPE, and to remove paper and other plastics from the HDPE.

Sorted Mixed Plastics. Mixed plastics (resin codes 3-7) separated from other materials by the MRFs either positively or negatively (i.e. allowed to fall into a bin after PET and HDPE had been removed). This stream was run through the optical sorting machinery to recover any PET and HDPE missed when the material was sorted initially, and to remove loose paper.

Unsorted Mixed Containers. Containers separated from fiber at the MRFs and transferred to a container sort-line for further separation. These containers were run through the optical sorting machinery to separate PET, PLA, and HDPE from all other material types.

MRF Processing Residuals. Contaminants and any containers remaining after desirable materials had been positively sorted at the MRFs from the mixed container stream. These residuals were run through the optical sorting machinery to recover PET, PLA, and HDPE that had been missed in the first sort.¹²⁰

Early sorts detected very little PLA in the samples, generally less than one percent by weight. To better test the ability of the system to distinguish PLA from other materials, the team “seeded” known quantities of PLA bottles and clamshells for additional trials on a variety of material streams.

Findings and implications

The results of the sorting trials varied considerably. At its best, the Pellenc/Titus system successfully detected 99.6 percent of the PLA bottles, cups and clamshells in the sample. In this case the machine was calibrated to separate only PLA from “other” materials in one pass. However, further trials at this setting were not conducted; some stakeholders at the follow-up forum doubted the result could be replicated consistently over time.

Other trials ranged from a low of 24 percent accuracy (explained mainly by heavy paper contamination that obscured the sensors and interfered with the air jets) to 97.5 percent of PLA containers correctly sorted. The findings varied with the level of incoming contamination and the configuration and number of separated fractions. Adjusting the machine to separate two fractions (PLA and something else) generally produced higher accuracy than three fractions.

The authors noted many factors may influence the performance of any optical separation equipment in the field, from the composition of incoming materials to the way in which infeed conveyors are loaded. Nevertheless, overall they found the mobile system to be a valuable tool when appropriately employed, “addressing a major challenge as bioplastic packaging grows in market share.” The team concluded

- When properly “tuned” to the incoming stream, the system could remove many contaminants from PET loads previously sorted at MRFs, thereby increasing the quality of marketed PET.

The study found such previously sorted loads, sold as “clean” PET bottles, actually contained more than 8 percent other plastics.

- The optical system could separate PLA bottles only, or mixed PLA bottles, cups, and clamshells from all other mixed containers at a MRF. This would allow recovery of PLA packaging for recycling into new PLA products, assuming adequate supplies and favorable economics.
- The team further determined the equipment can separate various plastic resins from each other, potentially allowing a MRF to recover valuable resins (especially HDPE and PET) inadvertently separated into the mixed plastic container stream. This could produce an additional revenue source for the facility. The authors suggested the extra sales may cover the additional sorting costs, although they did not analyze the costs and benefits.
- Likewise, running materials through the system a second time, or through two sorters in succession, would increase plastic recovery rates. This probably is not realistic for most MRFs due to throughput and space constraints. However, the authors suggest reclaimers should consider a second sort with a properly calibrated machine, since typically they already re-sort purchased bales to maintain quality control.

The stakeholder forum convened by Future 500 sparked a wide-ranging conversation on the end-of-life challenges for bioplastics and other new materials entering the California market. Some participants expressed skepticism in the likelihood of widespread adoption of optical sorters to effectively separate PLA and other new materials. Others noted the opportunities for capturing previously lost materials, including highly valuable HDPE and PET packaging.

The forum was not intended to establish consensus on the implications of the project findings, or indeed on the larger questions raised by adding materials to an established recovery structure. But collectively the group floated a number of policy and legislative suggestions for continued discussion. Some ideas specifically targeted California’s CRV program, such as increasing producer fees for bottles failing certain recyclability guidelines, reviving a plastic Quality Incentive Payment for MRF materials meeting stringent standards, and expanding the Plastic Market Development Payments. Other suggestions focused on broader, industry-wide approaches. These included establishing regional “intermediate” processing facilities around the state, employing advanced optical technology; establishing statewide MRF performance standards to reduce contamination; and increasing minimum recycled-content requirements for products made with certain resins.

The Future 500 project team concluded advanced separation technology like the custom system demonstrated in the Sorting Project will be critical in the coming years:

“By itself, enhanced optical sorting will not address the many challenges facing recyclers and processing facilities as new materials enter the marketplace. But the project demonstrated the feasibility of technology, when used under the right conditions, to increase both the effectiveness of the state’s recovery infrastructure and the quality of recycled feedstocks supplied to manufacturers fabricating new products and packaging.”¹²¹

Stanford: new possibilities for bioplastic recycling

As bioplastic materials increase their presence in packaging and products, at some point it becomes imperative to capture separate streams for degradable resins like PLA and PHAs. A true

cradle to cradle system would recover these plastics for recycling into products once again. But unlike advanced optical systems, this piece of the puzzle will likely involve technology of a different sort, emerging from the biochemistry laboratory rather than the drafting table.

A key component of the CalRecycle-funded research by the Stanford team examined recycling processes for PHAs and PLA.¹²² Rather than mechanical “washing and grinding” and remelting the resins into pellets, the usual method for recycling petrochemical plastics, Stanford’s proposed technique is to break down or depolymerize the collected bioplastics into their constituent monomers – a building-block approach. The building blocks would then be repolymerized into the complete resin, ready to be pelletized and sold back to manufacturers. Alternatively, the building blocks could be “re-arranged” to allow construction of different resin formulations.

The basic concept already has been employed to recycle PLA. The Belgian company Galactic has developed a “thermal depolymerization” process using hydrolysis (water-based decomposition) to recycle PLA commercially, breaking down PLA to purified lactic acid. The lactic acid then can be made into PLA again, or sold on the open market for use in solvents and other products. Galactic’s chemical recycling plant in Escanaffles, Belgium can process 2,000 tons of PLA annually.¹²³ Wisconsin-based Plarco uses the Galactic process to recover used PLA in North America (see details below).

Stanford’s charge was to investigate alternative approaches for depolymerizing PHAs and PLA without the use of toxic chemicals. Although a number of PHA producers have emerged in recent years, very little has been done to recover this family of resins after consumer use. As discussed, the first step in recycling, separating products into a homogenous stream, has its own challenges. But the hurdles are not unique to bioplastics. Assuming for the moment the sorting challenge can be resolved, the next step is converting the materials back into useful feedstock for manufacturing, ideally in a closed loop system (remanufacturing the same product).

The Stanford team approached the problem of recycling PHB (part of the PHA family) and PLA from several sides, including anaerobic digestion (AD), chemical and enzymatic hydrolysis, and thermal depolymerization.

PHB pathways

The first method used AD to break down the PHB polymer through biologic processes in the absence of oxygen, to produce methane. Tests indicated various resins in the PHA family significantly biodegrade in anaerobic digesters, and the conversion rate of plastic to biogas can be increased by including higher amounts of copolymer in the formulation. Then the Stanford process would start all over again using methanotrophic bacteria to produce PHB, as described in Part 1. Biocomposites of PHA and hemp demonstrated relatively rapid biodegradation rates as well when compared to composites using other compounds.

The team considered a second approach using chemical hydrolysis to achieve depolymerization. According to the authors, the AD route is less efficient, losing some carbon and energy to the metabolism of the microbes and other factors. As an alternative, the researchers used sodium hydroxide to break down the PHB to its monomers and then reassemble the hydroxybutyrate (HB) portion into PHB again. The researchers validated the reassembly process by feeding HB to bacteria from wastewater sludge in “feast-famine” pulses, then limiting nitrogen intake. This produced up to 50 percent PHB in the cells, on par with the yield rate achieved in Stanford’s methane-to-PHB process.

A third option explored by the group involved hydrolyzing PHB and its copolymer cousin in the PHA family, polyhydroxybutyrate-co-hydroxyvalerate (PHBV). Hydrolysis of PHBV in the Stanford laboratory yielded HB as well as the monomers hydroxyvalerate and crotonate. The researchers acknowledge crotonate is often considered a “dead-end product,” but note it can be polymerized into polycrotonates, “a class of polymers with highly tunable properties and a high melting point.” They are closely related to another set of polymers that includes the resin in Plexiglass®, and research at another Stanford laboratory suggests polycrotonates can be created from their monomers without harsh catalysts. Thus the authors conclude this third approach to recycling PHB/PHBV has the potential to tap a robust commercial market and a “major revenue stream” for recovered PHB.

Recovery of PHAs/PHB is by no means close to commercialization, of course. The Stanford laboratory research is very much in the early stages, and many links in the chain are speculative at this point.

Improving PLA recovery

PLA as a resin class is much further along in the marketplace, as discussed above. Limited recycling is already occurring commercially, though at a very small scale. Increasing that scale will require economic and technological advancements. CalRecycle therefore included a PLA recycling element in the contract with Stanford, to supplement the PHA research.

While the Galactic process hydrolyzes PLA down to lactic acid, the Stanford researchers hypothesized an alternative approach could break down the resin directly to lactide, bypassing the lactic acid stage. In theory this would be more efficient and could be accomplished without toxic chemicals, thus improving both the economics and environmental profile of PLA recycling.

The Stanford team studied two mechanisms to depolymerize PLA to lactide. Thermal depolymerization of PLA uses heat in the presence of a catalyst to break up the polymer. The researchers warmed PLA materials to 170°C-200°C with a tin catalyst until the boiling point was reached. Results showed lactide as the main product with a high degree of purity (above 94 percent). The recovered lactide then could become feedstock to manufacture new PLA and potentially lead to a more efficient method to recycle PLA products.

Stanford also examined biologically active enzymes to depolymerize PLA. The team collaborated with researchers at the University of Toronto to identify enzymes with PLA degradation potential. Twenty-two enzymes were found to depolymerize PLA to differing degrees. Of particular interest was an enzyme found in a marine bacterium and several other low-temperature enzymes, which potentially could have implications for PLA degradation in the ocean.

AD – the new kid on the block in California

Anaerobic digestion (AD) is part of the naturally occurring process of biological decomposition of organic matter. Anaerobic microbes thrive in conditions absent of oxygen, ultimately breaking down material into a biogas consisting of carbon dioxide and methane. Typically these conditions exist in swamps, sediment, the digestive tracts of cows and other ruminants, and elsewhere.

In the last few decades, this basic process has been used for treatment of wastes. In the U.S. variations of AD have been common in wastewater treatment, but for solid waste the technology has only recently begun to make headway. (Europeans, on the other hand, have been using the

technology for solid waste for some time.) Collectively, AD recovery systems represent another tool with promising end-of-life implications for degradable bioplastics.

An AD system generally includes one or more enclosed tanks or digesters which prevent oxygen from entering. Temperature is controlled throughout the process. Specialized handling equipment feeds organic material into the system at a consistent rate, and nutrients for the microbes are carefully controlled. The ratio of carbon (C) to nitrogen (N) is particularly important, requiring adjustment depending on the specific feedstock for the system. Organic MRF residuals, for instance, would require a different C/N balance than wastewater sludge.

Balance is fundamental to successful AD operations in many ways. The wrong C/N ratio can create ammonia that inhibits the desired bacteria. The pH generally must be kept at or near neutral (neither acidic nor basic); feeding the tanks too quickly can produce organic acids faster than they are consumed, resulting in conditions too acidic for the methanotrophs to thrive. Likewise, different microbial species require specific temperature ranges. And the percentage of solids in the feedstock must be monitored; solid waste digesters typically require the addition of water to the system. In theory, an AD system would produce just carbon dioxide and methane. In practice, AD may produce byproducts like hydrogen sulfide, ammonia and leftover digestate (which can be composted to create a soil amendment product).¹²⁴

One of the attractive aspects of AD technologies is their adaptability to various organic feedstocks. Collected bioplastics like PLA or PHA theoretically could be fed into an AD system to produce biogas as feedstock for the Stanford PHB process or to produce electricity, fuels or other chemicals. Moreover, degradable plastics mixed with food waste could be a viable AD feedstock, helping achieve the AB 341 imperative to divert organics from our landfills. And diverting wastes to AD contributes to California's climate change goals: by avoiding landfill methane that would otherwise be released to the atmosphere – a gas with a hundred-year global warming potential 25 times more potent than carbon dioxide¹²⁵ – AD turns an environmental liability into useful products.

At present in California, however, solid waste AD is in its infancy. CalRecycle is aware of at least thirty solid waste AD projects in various stages of development, construction and operation as of August, 2013. Interest in the topic continues to grow among local agencies that must divert ever-more material from landfills. Nevertheless, financing, permitting and other factors make AD systems challenging to implement.

In response, CalRecycle launched an Anaerobic Digestion Initiative to encourage the development of AD as an alternative to landfill disposal of organic material. Broadly the Initiative seeks to identify possible environmental impacts of AD operations and best management practices for reducing those impacts. It includes research projects, guidance for local agencies and AD operators, coordination with other State agencies, regulations for facility design and operation, technical work groups, and development of financing options.

In 2011 CalRecycle released a Program Environmental Impact Report (EIR) under the California Environmental Quality Act (CEQA), a tool to help local agencies evaluate AD proposals within their jurisdictions. The EIR is a comprehensive document providing point-by-point analyses of potential environmental effects of AD facilities and detailed measures for their mitigation that would be required of AD operators within the state. The report concluded “all the impacts could be mitigated to a less-than-significant level” and “AD facilities would have substantial benefits in

regards to diverting organic material from landfills and reducing greenhouse gas (GHG) emissions in comparison to existing practices.”¹²⁶

Additionally, the California Air Resources Board (CARB) is tasked with reducing the carbon intensity of California’s transportation fuels at least 10 percent by 2020. The CARB and CalRecycle evaluated the carbon intensity of fuel produced from AD and published a low carbon fuel standard “pathway” using High Solids Anaerobic Digestion. It is the lowest carbon intensity of any fuel pathway published to date (with a carbon intensity of -15 gCO₂e/MJ). It illustrates the potential of AD to produce low carbon fuel using pre-landfill, waste-based organic feedstocks.

These three technology innovations – advanced sorting, novel biochemical pathways, and anaerobic digestion – are still largely speculative at the commercial scale but potentially offer means of addressing the coming tide of bioplastics and other new materials.

Tweaking the materials

While the jury is still out for technological answers to bioplastic recovery, efforts are underway to reformulate the petrochemical plastics already in the marketplace. Much of the previous discussion centered on biodegradable plastics like PLA and PHA. But remember not all bioplastics are degradable. What if an already recyclable polymer could be biobased rather than sourced from fossil feedstocks?

Rethinking PET

This is the approach Coca-Cola and Pepsi have taken, based on the fact that a biobased resin can have exactly the same chemical formulation as one made from non-renewable resources, and therefore can be fully recyclable in traditional recovery operations. Currently about 30 percent of Coke’s PlantBottle is sourced from sugar cane and therefore “bioplastic,” but it is 100 percent PET just like its predecessors. It sidesteps the PET contamination problem altogether since the biobased monomer in the bottle is a “drop-in” ingredient, with properties identical to its petroleum counterpart. The current generation of PlantBottles, then, is simply blended petroleum-based and biobased PET.

Coke has separately introduced a biobased HDPE in its Odwalla line of juices. In this case, the bottle derives 100 percent of its basic monomer, ethylene, from sugarcane-based ethanol. However, HDPE has a much more limited use in Coke’s product line, due to its high gas permeability and opaque nature.¹²⁷

In 2011 PepsiCo announced that it, too, had developed a biobased PET bottle, but made entirely from renewable sources. The company indicated it had “cracked the code” for producing the main component in PET, terephthalic acid, from agricultural biomass like corn husks and pine bark. Ultimately, Pepsi plans to formulate the plastic using waste from its vast food production operations, including oat hulls and peels from oranges and potatoes.¹²⁸

Pepsi planned to pilot-test up to 500,000 bottles in 2012. The tests would include an evaluation of several technologies to create the TPA, particularly the ability to efficiently and consistently produce pure paraxylene, an essential TPA constituent. Costs and performance characteristics of the bottles would be analyzed as well.¹²⁹ However, the status of Pepsi’s biobased bottle was unclear at the time of publication. An October, 2011 report stated the company had not been able to produce the bottles beyond laboratory scale at the time.¹³⁰ The company had not released further details of its planned pilot as of October, 2013.

Pepsi's efforts notwithstanding, Coke's PlantBottle seems to have significantly affected the packaging world, four years after its 2009 introduction. In a June, 2013 statement Coke reported distribution of over 15 billion PlantBottles "and counting" in 25 countries, noting eight percent of its bottles were made with the formula by the end of 2012. The company's long-term goal is to convert all its PET bottles to PlantBottle packaging by 2020."¹³¹ Some analysts credit a significant portion of the recent double-digit growth in bioplastics market share to biobased PET, projecting global production capacity at 5 million metric tons in 2020, about 40 percent of the expected output for all biobased polymers.¹³²

Coke wants to rebuild an entire PET supply chain around the PlantBottle technology – and not just for its own products. It has licensed its technology to other major consumer goods companies, notably to Heinz for its ketchup bottles. Heinz reported distribution of 200 million bottles by 2013. Now Ford, Nike and Procter and Gamble have joined the two companies to form the Plant PET Technology Collaborative. The goal is a "100% renewable polyester plastic solution made entirely from plants for use in everything from clothing and footwear, to automotive fabric and packaging."¹³³

As Coke continues its quest for a fully recyclable, 100 percent biobased PET bottle, the company expects eventually to move from sugarcane to second-generation PET made from plant-based wastes like stems, fruit peels and bark. It has invested in the biotechnology companies Virent, Gevo and Avantium, each contributing research and development resources to the help the partnership achieve the 100-percent biobased goal. Virent, for instance, is using catalysts (substances that accelerate a chemical reaction) to convert plant-based sugars into platform chemicals like paraxylene, a precursor for the terephthalic acid (TPA) in PET. The company has plans to begin commercial production by 2015.¹³⁴

Gevo likewise is developing biobased platform chemicals, but from isobutanol produced with a proprietary fermentation process, using a yeast biocatalyst to convert sugars from various feedstocks. Gevo's strategy includes adapting existing ethanol plants to isobutanol production, taking advantage of low retrofit costs and "the ethanol industry's infrastructure and agricultural supply chain." It also has a partnership with Cargill to develop isobutanol from cellulosic sources like wood waste or corn stalks.¹³⁵

However, as discussed at the beginning of Part II, Avantium is taking a different path: 100 percent biobased polyethylene furanoate or PEF. PEF is a polyester similar to PET, but rather than combining monoethylene glycol and TPA as in PET, the ethylene monomer is paired with furandicarboxylic acid or FDCA (hence the "F" in the acronym). The resulting polymer is new to science, created with a patented catalytic approach Avantium has trademarked as its "YXY" process.¹³⁶

The PlantBottle strategy has been to create a package that does not disrupt PET recycling operations. But PEF raises new questions. If Coca-Cola and other major companies adopt PEF in a big way, the potential impact to recyclers becomes more conspicuous. What, exactly, are the thresholds of PEF that can be tolerated in a PET reclaiming operation? At what point will PET flake containing PEF change its critical characteristics, like melting point or intrinsic viscosity?

Furthermore, ASTM is considering modifications to its Resin Identification Code that would clearly define PET as the polymer produced from monoethylene glycol and TPA with only minor modifications allowed, thereby relegating PEF to the #7(Other) category. If California were to adopt that definition, large numbers of beverage bottles would move out of the PET category (#1)

and into the #7 slot. As discussed above, this could significantly affect the state's beverage container recycling program, since beverage manufacturers must pay Processing Fees according to the resin code of their bottles.

These sorts of issues have recyclers concerned. If PEF is not compatible with PET recycling at an industrial scale, the PlantBottle strategy could be negatively affected. On the other hand, complete integration into the existing PET reclamation structure – that is, complete intermixing of PET and PEF products and packaging regardless of the threshold held by either resin in recycling operations – would represent an opportunity to move from a fossil-based supply chain and into renewable feedstocks.

Will additives subtract?

Manufacturers are tinkering with plastic formulations on another front. Part I discussed the essential role of additives in plastic fabrication of “tuning” polymers for specific properties. Some companies are focusing on tuning traditional plastics with added substances to enhance the resins' environmental or economic profiles. The concept is to experiment with resin formulations or with the conversion process when manufacturing products, to see if the persistence in the environment of traditional resins can be mitigated.

Fillers and degradable additives are two ingredient categories relevant to this approach and to bioplastics' end of life. Fillers generally are inert minerals or other substances included in plastic formulations to reduce costs, improve strength or achieve other objectives. For example, calcium carbonate may be used in polyethylene plastics like HDPE. Virgin polyethylene has a low density, which recyclers exploit to separate polyethylene products from other more dense resins. The plastic products are ground into flake and fed into a “sink-float” tank where the polyethylene products float to the top for separation from other resins.

However, significant quantities of fillers in a formulation can change the physical properties of the plastic, reducing recyclers' ability to identify and sort plastics into clean streams. Adding calcium carbonate to polyethylene raises the density of the plastic; if too much is added, the density can rise above one kilogram per square meter and the products will no longer float.¹³⁷ HDPE reclaimers consequently lose a valuable stream of polyethylene, while reclaimers of heavier plastics like PET encounter more contamination and yield loss. The same principle holds true for bioplastics with densities similar to traditional resins; PLA, for example, will sink along with PET.

The second class of ingredients, degradable additives, presents greater implications for bioplastics and California's recovery system. These are substances added to petrochemical polymers to increase their ability to break down into smaller parts under specific environmental conditions. So a fossil-sourced PET bottle formulated with a degradable additive is still made from traditional plastic, but with new characteristics. The resulting resins are not bioplastics. Degradable additive manufacturers assert their products offer a more sustainable alternative to the fate of most plastic packaging, which is entombment in a landfill.

There are two general categories of degradable additives: those that are “oxo-biodegradable,” and additives with organic materials. Oxo-biodegradables use metals such as iron, zinc, manganese, magnesium, or cobalt in their formulation. The metals facilitate the scission (severing) of the long molecular chains in plastic polymers when they are exposed to sunlight and air. Manufacturers of

oxo-degradable additives claim the smaller plastic molecules then can be digested by microbes in the environment and biologically converted to non-toxic end-products.

Additives with organic materials utilize a different mechanism than their oxo-biodegradable counterparts to break down their plastic hosts, but claim to achieve the same results. These additives are melt-blended with the base plastic resins (such as PET or HDPE) during the plastic conversion process in manufacturing containers and other products. When the products come in contact with a biologically active environment, including conditions found in a landfill, the biodegradation process begins. Manufacturers of these additives claim microbes then can consume the organic material in the additive, creating a biofilm. This creates more surface area for other microbes to attack and ultimately break down the base plastic resin into humus and biogas – in other words, the plastic biodegrades.¹³⁸

Recyclers and composters in California and elsewhere have raised concerns over degradable additives.¹³⁹ The recovery industry is concerned over potentially detrimental impacts of these substances on their ability to process their materials. Moreover, they worry that the quality and safety of manufactured goods using recycled plastic or of compost products will be compromised.

While product manufacturers using degradable additives claim their products will convert to the material's most basic components (biogas, water, and organic matter) when discarded by consumers, the extent to which microbes will consume the smaller plastic polymer molecules is unclear. Plastics with degradable additives may simply fragment or break down into smaller pieces of polymer. As a result, metals and potentially toxic residues could remain in the environment.

Additive vendors have offered documentation of their claims, but recyclers and others do not believe the evidence withstands scientific scrutiny.¹⁴⁰ As described in Part I, some manufacturers making such claims have been challenged under truth-in-advertising laws. At this point, market adoption of these materials has been minimal in the U.S. But degradable additive manufacturers seem to be gaining traction in Europe and elsewhere. While uncertain at this time, the actual impacts to the recovery industry over the long term will depend on the level of market penetration achieved by producers using the additives.

In any case, the APR has issued guidelines for testing the effects of degradable additives on products made from postconsumer plastics. The testing protocols include requirements to expose the postconsumer materials to conditions that reflect actual treatment of recycled plastics by the recycling industry. Protocols for both PET and HDPE recycled materials have been established for postconsumer bales, fiber, bottles, strapping, and geotextiles.¹⁴¹

The additives controversy has direct implications for bioplastics, not least of which is general confusion by consumers over the difference between, say, a PLA clamshell and one produced from PET and oxo-biodegradable ingredients. That confusion spills over to non-degradable biobased resins as well, like the sugarcane-sourced portion of Coke's PlantBottle, which is chemically identical to its petrochemical predecessor. The burgeoning array of new materials may eventually show the way to more sustainable packaging and products, but in the short term that variety confounds the process. Moreover, the central issue raised by degradable – or “fragmentable” – substances is the same, whether for an inherently biodegradable polymer or one made from a petrochemical base resin: at end of life, does the material unacceptably contaminate our present recovery system?

Approaching from another angle

Several other “new approaches” are being explored to address the end-of-life challenges surrounding plastics.

Boosting markets

The PLA industry has attempted to jump-start recovery of its material in the U.S. by offering to purchase postconsumer and postindustrial PLA. BioCor, the company established for that purpose, began purchasing in 2010, partnering to capture such items as used stadium cups from the Oakland Coliseum in northern California. BioCor contracted with Plarco, Inc., a Wisconsin company, to process the collected material back into lactic acid. The Plarco plant uses hydrolysis, a type of chemical or “feedstock recycling,” to break down the PLA polymer with water into its constituent monomer lactic acid and other components. The recycled lactic acid is then sent to NatureWorks’ Nebraska plant to be polymerized into PLA again.^{142,143}

BioCor sent about 170,000 pounds of PLA to Plarco for conversion back to lactic acid in its first year of operation and about 230,000 pounds in 2011.^{144,145} But since then it is not clear how much is being captured on a regular basis. Nevertheless, the concept is important: if enough demand for the postconsumer material can be created, market forces will lead to recovery options. Naturally the price offered is critical; NatureWorks and its partners reportedly ponied up to support initial purchases of the material. Long-term, the viability of BioCor and similar ventures will depend on a variety of factors.

An example from the compost industry illustrates another market-based approach. Some composters have been proactive in assessing the compatibility of various bioplastics products with their operations. Cedar Grove, a compost facility near Seattle, Washington, has developed its own rigorous testing program for certain product types, like bioplastic cutlery and other food serviceware, in addition to requiring ASTM conformity and BPI certification. Products marked “Cedar Grove Compostable” with a brown band or label have undergone comprehensive testing in Cedar Grove operations.

The company even markets its own line of certified compostable packaging in addition to putting its stamp on scores of other brands. Cedar Grove works extensively with its suppliers and customers, including training and outreach to about 500 groceries, restaurants, and other food-service venues.¹⁴⁶ Some other composters have begun to accept Cedar Grove-approved compostables as a sort of de facto best-practice standard, although exact numbers are unknown.

The labeling of bioplastic items in the marketplace to clarify end-of-life options is the province of another organization as well: The Biodegradable Products Institute (BPI). BPI is a third-party certification organization manufacturers can apply to for compostability review. Testing on products is conducted by BPI-approved laboratories using established standards and testing, such as those from ASTM. BPI independently reviews the results, and if approved, the manufacturer may license the BPI “stamp of approval,” in *Figure 8* below.¹⁴⁷



Figure 8 – BPI compostability logo (copyright permission pending)

Others are working to address the market implications of bioplastics on other fronts as well, including the US Composting Council's Compostable Plastics Task Force and efforts by individual cities like San Francisco. Still others seek to transform the structure of markets altogether through producer responsibility or product stewardship initiatives.

The stew over stewardship

Efforts by Coke and Pepsi to move toward biobased bottles have been lauded on many fronts. Still, there are critics. Most do not argue with the logic of recyclable, biobased bottles per se; instead, they focus more broadly on other environmental considerations related to beverage packaging. Some contend the companies need to better address the end-of-life for their containers, including stronger support for recycling programs and using greater amounts of postconsumer resin in their bottles. Despite the virtues of recyclable biobased packaging, they say, the bottles are nonetheless designed for single use, doing nothing to address the negative environmental and economic impacts associated with littering or plastic ocean pollution.¹⁴⁸

The beverage industry counters it is indeed pursuing aggressive environmental goals, including company-wide sustainability initiatives to reduce energy, water and manufacturing waste. On the packaging front, Coca-Cola has announced a target of recycling 50 percent of its beverage containers by 2015, and 75 percent of the bottles and cans distributed in “developed markets” by 2020, including the U.S.¹⁴⁹

Other manufacturers are pursuing major packaging sustainability efforts as well. Most have “lightweighted,” or reduced the amount of resin used to manufacture their bottles. Pepsi reportedly has the highest percentage of recycled content across its product lines (10 percent on average) and has introduced 100 percent recycled PET bottles in its Naked Juice and 7UP lines in some markets.^{150,151} Nestle Waters North America markets some products in 50 percent recycled-content PET bottles. Along with Pepsi, Nestle partnered with Carbonlite to build a PET reclaiming plant in Riverside, California, capable of processing 100 million pounds of recycled bottles per year. The two beverage giants purchase most of the Carbonlite facility's output.¹⁵²

But despite these achievements, critics maintain voluntary efforts do not go far enough. They argue for mandatory programs to require end-of-life responsibility for containers and packaging, biobased or otherwise. Some advocate for container deposit legislation, “bottle bills” like those in California and nine other states. Others call for a more broad-based approach to packaging, mandatory Extended Producer Responsibility (EPR), where producers must pay for and implement recovery programs. While biobased products' reduced dependence on fossil resources is a step in the right direction, they say, significantly increasing plastic recycling and reducing

litter will require manufacturers to take life-cycle control of the products and packaging they introduce into commerce.¹⁵³

Europeans have had EPR mandates for packaging and various products for two decades or more. Canadian provinces have been expanding their bottle bills, moving from “shared responsibility” systems to full EPR for various products; British Columbia is the first jurisdiction in North America to require producers of packaging and printed paper to develop, implement, and pay the full costs for collection and recycling programs for these materials.¹⁵⁴ Many countries across the globe have adopted EPR for one product or another. California now has EPR mandates for carpet, paint, thermostats and mattresses.

EPR comes in many flavors. Indeed, there is a burgeoning literature on the subject – far beyond the scope of our discussion here – and it is increasingly becoming the subject of much study and debate in the U.S. For example, the U.S. EPA concluded a multi-stakeholder packaging “dialogue” in 2011 that explored a variety of financing strategies for end-of-life recovery of packaging, though EPR was not directly assessed.¹⁵⁵ Other groups have continued the discussion, notably the Product Stewardship Institute and San Francisco-based Future 500. The California Product Stewardship Council advocates EPR for many products. And CalRecycle is exploring a full range of packaging options in the context of California’s 75 percent recycling target.

Beverage companies have long opposed container deposit legislation, and consumer goods companies more broadly have resisted mandatory EPR programs. While EPR has been slower in coming to America than in European and other countries, there are already more than 80 state producer responsibility laws covering a wide range of products (primarily hazardous items) in 33 states.¹⁵⁶ Nevertheless, the flurry of packaging recovery conversations seems to be raising the profile of this approach around the country. Notably, Nestlé Waters North America has publically endorsed the concept.¹⁵⁷ The company supported stakeholder meetings convened by Future 500 which have now materialized into a formal organization, Recycling Reinvented. The group seeks to be “a place where industry, government, and nonprofit organizations can come to find out how EPR works, how it can increase recycling rates, and what will be required to make it work.”¹⁵⁸

EPR advocates assert that thoughtfully-designed EPR approaches can lead to better choices by producers when designing and introducing new products, packaging and materials into the marketplace, since they must pay for end-of-life disposition. The concept is called Design for the Environment (DfE) or Design for Recycling (DfR). In essence, DfE principles call on designers to plan for the recovery of their products right from the start, by using less material up front, using more easily recycled materials, allowing for easy disassembly, using materials with lower carbon footprints, and the like. While groups such as the Sustainable Packaging Coalition have voluntarily promoted DfE for their members, EPR advocates would like to see such efforts institutionalized through mandatory means. They argue mandatory EPR “levels the playing field” for all producers in a sector and reduces government intervention to oversight and enforcement functions.

Environmental Profiles of Plastic Packaging

Life cycle assessments (LCAs) use a science-based approach to estimate the impacts of materials and processes on the environment and human health. LCAs can be performed to help understand the environmental profile of plastic packaging and to pinpoint specific materials and processes that deserve close attention when evaluating trade-offs and selecting packaging materials. DTSC commissioned several CalRecycle-funded life cycle studies to evaluate the resource requirements

and environmental impacts of a few different types of plastic resins used to make bottles. The intent was to analyze the environmental impacts of the production and recycling system of PET bottles in California and compare it with the environmental impacts of the production and recycling of PHB bottles based on deployment of Stanford's PHB process at a commercial scale in the State.

A comprehensive LCA for the established PET bottle industry was performed by UCSB researchers. UCSB's LCA included feedstock extraction, processing, PET pellet production, bottle manufacturing, transportation to the consumer, and end-of-life management either via recycling or landfill disposal. This was a "cradle-to-grave" LCA because it examined the inputs, outputs, and mass flows for all processes associated with the product, including end-of-life impacts beyond early "cradle-to-resin" phases.

Stanford researchers conducted a "cradle-to-resin" LCA which, unlike the UCSB LCA, did not include the consumer-use phase of the product or the end-of-life management of PHB bottles. The Stanford LCA evaluated the production of PHB by methanotrophs from waste biogas. The LCA was based on extrapolation of laboratory data to estimate the environmental impacts of commercial-scale production of PHB. Stanford's LCA focused primarily on the early stages of polymer production and the environmental impacts of different PHB recovery methods.

Presented below are summaries of the contractors' findings. Additional details on the LCAs are available in the individual contractor reports accessible via CalRecycle's publications catalogue.

LCA of PET Beverage Bottles in California (UC Santa Barbara)¹⁵⁹

Overview of Scope

Researchers at UCSB conducted a cradle-to-grave LCA which analyzed PET bottle production and recycling in the State based on data from 2009. They modeled a baseline which represented the annual production and consumption of single-use CRV PET bottled beverages in California. The baseline scenario assumed that an average bottle contained 3.9 percent recycled resin and a large portion of the recovered bottles were exported. Additionally, the researchers modeled another scenario where both recovery of PET bottles and reclamation of the secondary materials all occurred in California with no exports (the "California-only" scenario). In this scenario, it was also assumed that all bottles were produced with 15 percent recycled content with no changes to the recycling rate.

The PET LCA was based on published literature and available inventories as well as interviews and site visits to California facilities. A total of 21 impact indicators were evaluated, including 8 environmental indicators and 13 toxicity indicators.

Key Findings and Recommendations

The researchers found the majority of environmental impact categories occurred in the raw materials extraction, processing, and manufacturing stages, primarily due to air quality impacts from energy demand. Other findings included:

- In all scenarios materials recovery – including recycling center, curbside, and MRF operations and consumer travel to drop-off locations – made a small contribution to environmental impacts in general.

- In the California-only scenario, with no export of recycled PET bottles, there was a significant reduction in transportation emissions.
- In all scenarios recycled PET (RPET) production showed lower environmental impacts compared to the production of virgin PET.
- The toxicity impacts are an unreliable basis for comparison of the scenarios due to uncertainties and variability in the underlying inventory data sets that were utilized in the LCA.

Data Gaps and Study Limitations

Although the authors were able to use raw data for some aspects of the production processes and available inventory data for energy, there was no “authoritative” process inventory for solid waste disposal in California or the U.S. at the time of the study. In these instances, the researchers used Swiss (Ecoinvent) LCI data which is representative of conditions in Switzerland and differ significantly from the waste management practices in California.

LCA of methane-based PHB (Stanford University)¹⁶⁰

Overview of Scope

Stanford researchers conducted a “cradle-to-resin” LCA which, unlike the UCSB LCA, did not include the consumer-use phase of the product or the end-of-life management of PHB bottles. The Stanford LCA evaluated the production of PHB by methanotrophs from waste biogas. The LCA was based on extrapolation of bench-scale data to estimate the environmental impacts of commercial-scale production of PHB. Stanford’s LCA focused primarily on the early stages of polymer production and the environmental impacts of different PHB recovery methods. Stanford evaluated a total of 9 environmental impact categories.

Key Findings and Recommendations

Most environmental burdens stemmed from energy used in the system to produce PHB. Other findings included:

- The extraction techniques, or “recovery methods,” had the largest environmental impacts. Use of solvent extraction for PHB recovery resulted in a majority of the environmental impacts for each of the 9 impact categories analyzed.
- Selective dissolution was shown to have fewer environmental impacts than other extraction methods.
- The total energy requirement for PHB production from waste biogas is lower than from corn feedstocks.
- Biogas derived from the anaerobic digestion of waste PHB plastic products and residual biomass from PHB production can offset the energy requirements to manufacture PHB.
- The authors recommended that future research efforts should be focused on finding a less energy-intensive extraction method that is not solvent-based.

Data Gaps and Study Limitations

Bench-scale data were extrapolated to estimate energy use in the system as no data from industrial scale production of PHB from waste biogas were available. Additionally, due to limited supply-chain data, best estimates were used to evaluate the impacts of biochemical products needed for PHB production. In addition, the authors assume that methane from biodegradation of PHB products will be captured and returned to the system; however, the infrastructure is not yet in place to recover PHB.

LCA of PHA from MRF residuals (UC Davis)¹⁶¹

UC Davis researchers evaluated the potential environmental impacts of producing PHA bioplastics in California using the organic fraction (biomass) from materials recovery facility (MRF) residuals. The study evaluated a multi-line biorefinery which included one line to produce PHB from methane and two separate lines that would ferment sugars from MRF residuals to produce PHA. A biorefinery of this size and complexity did not exist at the time of the study. Thus, the underlying datasets for the specific design of this biorefinery were not available and best estimates were relied upon for the analysis. The model included “pre-fermentation” (sorting and hydrolysis of organic residuals), “post-hydrolysis” (solid-liquid separation and flash distillation) and “fermentation” life-cycle stages.

To perform this preliminary analysis of using waste to make bioplastics, partial information was pulled from five published LCA studies that evaluated different stages of PHA production using a variety of processes and feedstocks. The results of this research were inconclusive as it was based on numerous assumptions and technologies that have not been integrated into a biorefinery.

Review of LCA Studies (UC Berkeley)¹⁶²

UC Berkeley was contracted to confirm the other university LCAs incorporated scientifically acceptable methods, followed established best practices for conducting an LCA, included results that reflected the project goals, clearly stated study limitations, and were transparent. UC Berkeley found that each LCA was conducted in accordance with the established scopes and goals, and followed acceptable practices. Importantly, the UC Berkeley review found the LCA studies should not be used to compare the plastic and bioplastic resins to one another due to the uncertainty in the underlying data sets and different system boundaries used to conduct the LCAs.

Limitations of LCAs

There are limitations to the LCA studies that merit attention and consideration – many of which center around the integrity of the data used to perform them. While the LCAs offer a glimpse at possible effects on the environment directly attributable to manufacturing processes and delivery of the plastic products studied, these studies do not provide definitive results. When conducting any LCA, data is nearly always the limiting factor and these LCAs were no exception. In order to accurately catalogue the environmental and economic impacts of every stage and every entity in the lifecycle of a plastic product the LCA requires a very large amount of data. Despite best efforts by the contractors, some of the critical data needed for these studies were

unavailable. Therefore, in order to allow for a complete analysis, certain assumptions needed to be made to bridge the gap between the data needed and the data available.

Some of the limitations of these LCA studies include:

- The results of LCAs are based in part on the geographical locations from which the datasets and process inputs and outputs are inventoried. All three studies relied in some part on the Europe-based Ecoinvent database which may not reflect California conditions.
- LCAs assess potential impacts but may not factor in certain actual impacts or space and time considerations. For example, these LCAs did not evaluate the environmental impacts of littered plastics, exposure to toxins released by materials outside the study boundaries, depletion of fossil resources compared to renewables, or California resource availability, such as water supply and quality in the state.
- The age, accuracy, and availability of the data and the impact assessment methods used have a significant bearing on LCA results. In all three LCAs data gaps were identified. The PHB LCAs relied on experimental data, assumptions and best estimates. The PET LCA showed widely variable and inconclusive toxicity impacts due to conflicting underlying data sources.
- Other challenges in the practice of LCA include methodological issues such as appropriate measurement of credits for avoided environmental burdens (e.g. allocation of recycling processes in the analysis of PET) and accounting for potential benefits of jointly produced outputs at a facility, as in Stanford's assessment of PHB co-produced with electricity.

Debate has surrounded the proper and effective use of LCAs in reaching “definitive” measurements of a product's environmental impacts – especially when comparing similar products or materials such as plastic resins. The LCAs detailed here point to areas for improving certain life-cycle processes, which could result in fewer impacts on the environment, but they do not provide a comparative analysis of the materials.

Bioplastics and Marine Debris

A final note regarding the environmental profiles of bioplastics concerns ocean litter or marine debris. As noted in this report, the Ocean Protection Council's (OPC) 2007 marine debris resolution in part prompted the CalRecycle-funded bioplastic research projects described here. Degradable plastics are an active area of research. One goal is to determine if degradable plastics can help address the problem of increasing plastic debris accumulating in the North Pacific Gyre (a zone in the Pacific Ocean), by being designed to break down harmlessly in the environment.

Many consequences of plastic litter are well-documented, such as wildlife ingestion and entanglement, clogged municipal storm drains and cleanup, and plastic pellet pollution. Now scientists are focusing research on additional concerns: the unknown impacts of micro-sized plastics and potential risks that may be posed by bioaccumulation, as well as the transport of invasive species and environmental pollutants by plastic debris in the ocean.

Furthermore, evidence of toxins from plastics in the marine environment is growing. In 2011, the OPC and its partners published a report documenting recent research on the impacts of plastic debris. Researchers have found high percentages of potentially toxic compounds in marine debris

samples, including polychlorinated biphenyls (PCBs), compounds used in manufacturing plastics and other products which are toxic to aquatic life and persist in the environment for long periods; polycyclic aromatic hydrocarbons (PAHs), which are byproducts of combustion processes; and various pesticides. But toxicological impacts of plastic debris and risks to humans are still largely unknown and under investigation.

What is clear is that it is in the best interest of California's economy, environment and public health to *prevent* plastic waste – petrochemical or otherwise – from reaching the natural environment. Recovery and reuse of materials, including efficient handling of postconsumer waste, is a critical focus for achieving reductions in landfill tonnage and ensuring the capture of plastics.

Bioplastics may play a role in this endeavor, but some of the proclaimed benefits of these materials are not yet apparent. It is also unknown how additives in bioplastic products or use of chemicals in the production process of biopolymers may impact the environment during the degradation process. Until more is known, these innovative materials are deserving of consideration and additional research but are not in and of themselves a solution to ocean litter or marine debris.

PART III – Lessons Learned

The object of this report has been to ascertain and explain our current understanding of bioplastics and packaging in the California marketplace. Parts I and II presented the findings from several CalRecycle-funded university studies, striving for technical accuracy while presenting the research and issues in an understandable fashion for a wide audience. They explained the complexity of integrating new materials into existing systems, from the “cradle” to end-of-life disposition.

When CalRecycle initially funded many of the projects five years ago, a broad-based understanding of the implications of bioplastics was beginning to emerge. While it still is, a great deal of knowledge has been gained since that time. This portion of the Report summarizes CalRecycle's perspective on lessons learned.

What the research tells us

Below is a brief summary of pertinent findings from each study.

Stanford laboratory research on producing PHB from waste methane

The Stanford team explored multiple facets of the quest to produce and recover PHB from waste, by manipulating bacteria found in nature, without genetic engineering. Some key results:

- The researchers produced small quantities of methane-based PHB in the laboratory, but did not reach the pilot-testing phase necessary for scaling up to commercial production.
- Type II methanotrophs (bacteria) produced PHB most efficiently, which could be enhanced through careful control of growth conditions. Pulsing the amounts of available nitrogen and methane – the “feast or famine” approach – turned out to be the most important factor for enhancing PHB production.

- Mindful of green chemistry principles, the team explored less-toxic alternatives to chloroform for extracting PHB from the cell biomass, a critical stage of the production process. Supercritical carbon dioxide appeared promising, but tests showed it did not adequately extract the polymer from the bacterial cells. The team settled on a combination of a surfactant (sodium dodecylsulfate, or SDS) and a solvent (hypochlorite) as the best method balancing an effective, low-cost recovery process with reduced toxicity and polymer stability.
- The researchers conducted initial tests on the plastic's potential for consumer packaged goods and construction materials. The team paid special attention to performance attributes for both the in-service (consumer use) and out-of-service (degradation or other disposition after use) stages of product lifecycles. Preliminary findings suggest PHB co-polymers, blends or biocomposites (combining PHB with other natural materials like hemp) show promising attributes.
- Finally, Stanford's team conducted laboratory experiments on the potential for enhanced end-of-life recovery of products made with PHB and PLA. They examined anaerobic digestion of PHB, PLA and biocomposites, as well as enzymatic and thermal depolymerization techniques for breaking down the bioplastics to their chemical constituents. This, in theory, could allow a full cradle-to-cradle system, where the recovered "building blocks" could once again create new plastics.

UC Berkeley economic analysis of manufacturing the Stanford PHB in California

UC Berkeley researchers developed a statewide overview of the cost drivers and economic conditions in California for producing PHB with the Stanford process, calculating the Net Present Worth (NPW) of a small hypothetical plant co-located with a methane source like a landfill or wastewater treatment facility. Main findings:

- A thorough market-related literature review found strong support for the notion that bioplastics in general are poised to experience significant growth to 2020 and beyond, though their market share is still small compared to petrochemical plastics.
- The team estimated 49 landfills and 10 wastewater facilities in California have enough biogas available (that is, methane not otherwise contracted for) to support a plant producing 1,000 metric tons per year.
- Modeling suggests a plant of this modest scale may be profitable (have a positive NPW) under reasonable assumptions for PHB yield, energy requirements, equipment, operating expenses, and PHB market price. Using baseline values for these factors, the team found a positive NPW for any PHB price over \$0.53 per pound.
- The authors acknowledged great uncertainty in the data underlying their modeling, as the Stanford process has not been implemented commercially.^{§§§§§} They conducted sensitivity analyses for key cost drivers to determine the effects of data variation on the end results. Extraction costs and PHB selling price were most sensitive to higher-than-baseline scenarios,

^{§§§§§} A California company called Mango Materials has licensed the technology from Stanford, but at publication time had not produced the bioplastic at industrial scale.

meaning those areas should be vetted especially thoroughly when expanding the Stanford process to commercial scale.

Stanford study of PHB production costs

The Stanford group projected production expenditures for a commercial venture based on their laboratory research, providing another economic angle on the project. The authors compared biogas-derived electricity production with using waste methane to manufacture PHB instead. (Again, data are uncertain; the results should be treated as “ballpark” estimates.) Highlights:

- The Stanford researchers found PHB production potentially could generate more revenue than electricity per unit of biogas, as long as PHB sells for more than \$2 per kilogram (\$0.91 per pound).
- The low cost of waste methane feedstock improves profitability. Stanford’s calculations suggest producing PHB at medium-sized plants (5,000 tons per year or less) may be feasible at a price competitive with common petrochemical plastics. At about this size, projected plant costs begin to level out, incurring proportionately fewer additional expenses per ton compared to larger facilities.
- In small plants (less than 2,000 tons per year), labor represents almost half the costs for operating a facility, whereas electricity becomes the biggest expense for plants larger than that, at about 40 percent of total operations. Electricity costs could be mitigated if a portion of the on-site biogas is redirected to power the plastic manufacturing plant.
- The team estimated most California landfills hypothetically could support PHB production of 2,000 tons or more per year, and 13 sites could support manufacture of greater than 10,000 tons per year.

UC Davis economic model of producing PHA from MRF residuals in California

UCD researchers modeled the economic feasibility, optimal size and best California location for a hypothetical PHA facility, using organic MRF residues as feedstock (rather than methane). The modeling suggests:

- Martinez, California (in the San Francisco Bay Area) would be the best location for such a PHA plant, drawing on residuals aggregated from surrounding MRFs.
- An “optimal” plant, economically speaking, would produce about 148 million pounds of PHA a year, but would be extremely expensive to build. Given the major financial risk in constructing a plant that size, UCD examined a smaller facility producing about 34 million pounds per year. Still, his model suggests such a facility would require a capital investment of more than \$300 million, with PHA selling at about \$2.73 per pound (\$6.00 per kg).
- Extremely limited data constrained the research. This required the researchers to make “educated guesses” about many data points necessary to model the untested technologies for the hypothetical PHA plant. Once again, results should be viewed as suggestive only.

Lawrence Berkeley National Laboratory analysis of potential leaching in plastic water bottles

The LBNL team quantified chemicals potentially present in water packaged in PET and PLA bottles from various manufacturers at different temperatures and storage times, including plastic additives, and developed a preliminary exposure assessment of chemicals found to migrate from the bottles into the water. The authors determined:

- None of the chemicals found in either PET or PLA bottles pose an immediate concern for public health as they were measured in the water during the storage and temperature tests.
- A total of twenty-nine organic compounds and twenty-four chemical elements were identified and measured in the storage trials for the PET and PLA bottles. Most of the organic compounds had average concentrations less than 0.1 parts per billion (ppb) and only seven rose above this value when stored for 6 months at 35°C. The concentrations of all compounds ranged from less than .001 ppb to approximately 1 ppb during this test.
- A distinct trend was determined for increased concentrations of compounds in both the PET and PLA bottles for higher temperatures and longer storage times. Specifically, compounds in PET bottles on average increased by a factor of 9.4 for every 10°C increase in temperature over a 6-month storage period. Correspondingly, compounds in PLA bottles on average increased by a factor of 7.2 under the same conditions. A more muted trend in increasing compound concentrations was found for longer storage periods.
- The list of prioritized chemicals for health hazard assessment included seven compounds, including a phthalate (diisobutylphthalate, a known endocrine disruptor) and benzophenone (a known carcinogen), and two elements (antimony and tin). Most of these prioritized chemicals showed increased concentrations for both higher temperatures and longer storage times.
- The exposure assessment included the calculation of the concentration of each prioritized chemical under typical storage (3 months) and temperature (35 °C) conditions. From these values, the estimated human exposure of the prioritized chemicals was determined for children and adults using the mean and 95th percentile daily water intake rates.
- Despite the fact that no standard limits have been established for these chemicals in water, the preliminary health assessment of the prioritized chemicals found that the concentrations were too low to pose a significant risk to human health.

UC Santa Barbara LCA of PET beverage bottles sold in California

UCSB researchers conducted an LCA analyzing a baseline and two variants of PET beverage bottle production in 2009, plus a hypothetical model where bottles would be recovered and recycled (at 15 percent recycled content) within California. They found:

- In all scenarios materials recovery – including recycling center, curbside, and MRF operations and consumer travel to drop-off locations – made a small contribution to environmental impacts in general.
- In the California-only scenario, with no export of recycled PET bottles, there was a significant reduction in transportation emissions.

- In all scenarios recycled PET (RPET) production showed lower environmental impacts compared to the production of virgin PET.
- The toxicity impacts are an unreliable basis for comparison of the scenarios due to uncertainties and variability in the underlying inventory data sets that were utilized in the LCA.

Stanford LCA of waste methane-based PHB

The Stanford team performed an LCA of PHB produced from waste methane, based on a cradle-to-cradle life cycle where PHB products are recovered and biodegrade back to methane. The authors projected:

- The extraction techniques, or “recovery methods,” had the largest environmental impacts. Use of solvent extraction for PHB recovery resulted in a majority of the environmental impacts for each of the 9 impact categories analyzed.
- Selective dissolution was shown to have fewer environmental impacts than other extraction methods.
- The total energy requirement for PHB production from waste biogas is lower than from corn feedstocks.
- Biogas derived from the anaerobic digestion of waste PHB plastic products and residual biomass from PHB production can offset the energy requirements to manufacture PHB.
- The authors recommended that future research efforts should be focused on finding a less energy-intensive extraction method that is not solvent-based.

CSU Chico PHA bottle development

CSU Chico experimented with three commercially available bioplastic resins to determine the best operating parameters for blow-molding high-quality bottles using existing equipment and techniques. (The Stanford PHB had not yet been produced in sufficient quantities to conduct the tests.) Major findings included:

- Overall, the Metabolix resin outperformed those from Chinese producers Tianan and Tianjin. (Metabolix was still producing its *Mirel* PHB at the time of the study; subsequently its U.S. plant closed.)
- The tested resins were best suited for one-step extrusion blow-molding rather than a two-step, stretch blow-molding process. Thus, the PHAs can be shaped into bottles known to use the extrusion process, such as shampoo or detergent plastic bottles. They are not as well suited for water or soda bottle applications.
- A few prototype bottles were included in optical sorting trials during the CalRecycle-funded Future 500 project. Anecdotally it appears the bottles could be properly detected by the optical technology, although systematic testing was not done.

CSU Chico analysis of PLA and PHA biodegradation in marine environments

CSU Chico also examined bioplastic degradability in marine conditions, testing samples of PLA and PHA in California seawater using ASTM test methods and specifications for marine degradation of plastics. The results indicated:

- The rate of biodegradation for *Mirel* PHB was fairly high, exceeding the 30 percent carbon conversion rate the standard required over a six-month timeframe. However, the ASTM protocols call for temperatures of about 86°Fahrenheit, much warmer than typical Pacific Ocean temperatures averaging around 55-65° Fahrenheit.
- PLA exhibited very limited degradation over the 6-month testing time frame. (Note PLA typically is designed to be industrially compostable, not degradable in the ocean.)
- Toxic chemicals or byproducts were not released from the samples during the degradation process. However, toxicity testing was limited, and comprehensive toxicity tests of marine organisms were not conducted.

Future 500 pilot-testing of optical technology for sorting PLA

The Future 500 Bioplastics Sorting Project tested removal of bioplastic bottles and packaging from 11 facilities and several waste streams around California with near-infrared optical technology developed by Pellenc Selective Technologies of France, using a mobile system built for the purpose. The project scope did not include a cost analysis. The team determined:

- Initial sorts found very little PLA in the sampled recycling streams, less than one percent by weight. (Later trials included samples “seeded” with known numbers of bioplastic containers.)
- Results varied considerably; at its best, the system successfully detected 99.6 percent of the PLA bottles, cups and clamshells when the machine was calibrated to separate only PLA from “other” materials in one pass. However, further tests under these conditions were not conducted.
- When properly “tuned” to the incoming stream, the system could remove many contaminants from PET loads previously sorted at MRFs, thereby increasing the quality of marketed PET.
- Conversely, the optical system could separate PLA bottles only, or mixed PLA bottles, cups, and clamshells from all other mixed containers at a MRF. This could allow recovery of PLA packaging for recycling into new PLA products.
- The equipment could separate various plastic resins from each other, potentially allowing a MRF to recover valuable resins (especially HDPE and PET) inadvertently separated into the mixed plastic container stream.

Introducing new materials: the front end

California's new imperative to reduce, recycle or compost 75 percent of its discards by 2020 heightens the need to foster economic innovation, to stimulate new thinking and technology and to create new opportunities from resources previously considered “waste.” With the findings from the various studies in mind, several implications for the production of bioplastics in California emerge – and perhaps for other new materials and packaging as well.

- *Producing useful materials from waste in California could offer new options for reducing disposal, lowering greenhouse gases and creating jobs, but should be evaluated with the end of life in mind.* The work at Stanford suggests a powerful greenhouse gas may be turned from an environmental and economic liability into an asset. Of course, the research is preliminary. Complex supply-chain logistics have yet to be worked out – not least of which is the recovery of used PHB products to cycle back into the system – but the potential benefits should be considered. Moreover, substituting a naturally-occurring material for petrochemical plastics may reduce our dependence on oil, and could even play a role in diminishing the effects of marine debris. However, much work needs to be done on many fronts to ensure waste-based materials do not have unintended consequences.
- *Producing bioplastics in a closed-loop system may be possible, but requires the concerted efforts of many actors throughout the product life cycle to avoid disruption of existing recovery programs.* This includes research and development, pilot-testing, evaluating commercial-scale manufacturing and establishing used-product recovery – and feedback between stages and stakeholders. Stanford’s research offers early evidence PHB can be adapted for commercial applications like packaging or construction, but the full “loop” has a long way to go. Support by key participants can tilt the scales; witness Coca-Cola’s biobased PlantBottle, which is challenging the fossil-based packaging supply chain status quo without disrupting existing recycling channels.
- *Small-scale, regional plants using waste as feedstock may be viable alternatives to large manufacturing facilities.* Conventional thinking may assume very large manufacturing plants will gain so-called economies of scale, lowering per-unit costs and generally improving competitiveness. But the UC Berkeley and Stanford economic assessments of the Stanford PHB, though preliminary, suggest small facilities co-located with the feedstock source and a means to recover the used bioplastic may offer a feasible option and require significantly lower upfront investment.
- *The CalRecycle-funded environmental studies clearly rely on many uncertain data points and should be viewed with caution, but they do suggest new models for lowering the impacts of producing plastics.* The Stanford LCA cannot be directly compared to analysis of a mature production system, like the PET study from UC Santa Barbara, nor should an LCA be considered the last word on the environmental consequences of any material, product or package. Nevertheless, the research raises possibilities for capturing both economic and environmental value from used materials.
- *There is no “one size fits all” approach to tackling the effects of plastic waste.* “Bioplastics” are not a monolithic class of materials; rather, the list of biobased and biodegradable polymers is wide and varied, requiring separate evaluations of benefits and costs. Each new technology brings unique considerations to bear; advantages under one scenario can become liabilities under another. Still, creating value-added polymers from recovered materials within our borders may offer new opportunities for California as we move toward the 75 percent goal, if we can resolve conflicts with existing recovery systems.
- *From an environmental perspective, preferred applications for bioplastics are unclear.* As implied above, perhaps the better question to ask is *which* materials under *what* conditions offer the greatest potential for reducing the environmental burdens of business-as-usual. For instance, certified compostable bags produced from residual organics or anaerobic digester

gas could prove to be a boon for collecting more food waste, addressing AB 341 objectives on two fronts simultaneously. Conversely, encouraging manufacture of bioplastics from food crops, without a recovery strategy, may do little to lower overall environmental burdens and could even jeopardize the very activities critical to achieving the state's goals. Collectively we still have much to learn about the delicate balance between entrepreneurial innovation and environmental preservation.

- *Bioplastics are not “the solution” to litter or the marine debris problem.* Some have touted degradable plastics in particular as an alternative to petrochemical resins that may persist in the environment. In some respects certain bioplastics may turn out to be preferable options. But there is no silver bullet. Litter and ocean pollution are complex problems with multiple facets. There is simply too much still unknown about the interactions between different resin formulations, additives, bioaccumulation potential and the like to suggest a solution is at hand.

Introducing new materials: the back end

Our foray into producing bioplastics in California brings home a singular message, if nothing else: simply manufacturing a new material is not enough. Producers – indeed, everyone along the supply chain, consumers included – need to consider what happens on the back end as well. The research in this report highlights critical questions we must ask about recovering the packaging and product innovations entering the California market. Ideally the lessons learned will enhance rather than impede our journey toward 75 percent and beyond.

- *Separation is key.* Effective recovery of bioplastics, or any material, frequently boils down to one thing: sorting. It is the Achilles' heel of the recovery loop. Inadequate sorting leads to cross-contamination, yield loss and economic uncertainty, as we have seen. Without a plan on the back end to pull them out, materials newly introduced in the marketplace can plague recyclers and composters – witness the outcry over PLA bottles. Likewise, effective recovery of new materials themselves depends on their separation for further processing.
- *Improved separation technologies will require research and investment.* At the risk of stating the obvious, we emphasize the need for continuous technological improvement as more and more material variations come down the pike. The Future 500 sorting project, while not the last word on bioplastic separation, does highlight the potential for advanced optical sorting to segregate incompatible materials and improve the recovery of each. Of course cost is an issue, but that may be brought down through research and market competition. The glass industry is instructive here: early optical sorters (mostly from Europe) were extremely expensive, but improved technologies funded privately and publically (including through CalRecycle grants) have brought costs down and efficiencies up.
- *Regional plastic processing facilities may offer market efficiencies to enhance material recovery.* One of the suggestions emerging from the Future 500 project was to establish intermediate processing plants, where commingled plastics could be consolidated and separated more effectively before shipment to reclaimers. This might allow greater investment in improved sorting, reducing yield loss and improving overall recovery economics. Just how this might be accomplished, or whether such facilities would actually lower costs, is yet to be determined.

- *Closed-loop venues can be useful testing grounds for introducing and recovering new materials.* Some packaging brand owners have introduced bioplastics into general commerce without adequate arrangements for postconsumer capture. In contrast, closed-loop venues such as stadiums, university cafeterias, and festivals offer the chance to monitor both the front and back ends of product introduction. BioCor, the PLA recovery organization, has experimented with collecting PLA cups from the Oakland A's baseball team and shipping them to a reclamation facility. This allows evaluation of logistics, contamination levels and other factors critical to establishing recovery systems.
- *Link market forces with “seed” money to jump-start recovery operations.* The essential concept behind BioCor is that market demand for postconsumer PLA will spur new recovery efforts, eventually establishing a stable recycling loop. The BioCor founders evidently contributed funding to pay for initial purchases and reclamation of scrap PLA. While the long-term viability of BioCor is unclear, the concept has merit. The unsettled element, of course, is how much upfront investment is required before a recovery system can survive on its own, and who should foot the bill.
- *Improved labeling can help educate consumers about the differences between bioplastic categories and help support recovery infrastructure.* The FTC has tightened its guidelines for environmental marketing claims, California has established new standards for the “biodegradable” designation on plastics, the Sustainable Packaging Coalition has piloted uniform on-package recycling information and ASTM is fine-tuning the Resin Identification Codes. These efforts and more may reduce confusion around the many new materials in California and usher in more robust recycling and composting systems.
- *Enhanced recovery technologies for bioplastics could be on the horizon.* Stanford's early research into PHA depolymerization techniques and many efforts by private companies point to emerging end-of-life options. Notably, anaerobic digestion, common in wastewater treatment, offers new opportunities for recycling biodegradable polymers. The concept of “platform chemicals” is important as well – there may be options to safely break down biopolymers and return their constituent monomers to the industrial pool, to be fashioned into useful materials once more.

In conclusion

In this report we have explored the multiplicity of challenges sparked by new bioplastic packaging and products in California's dynamic marketplace. Bioplastics are likely to increase – that much seems clear. But they are not unique. Packaging is constantly changing; new materials are continually introduced. Our recovery framework must adapt to remain sustainable. At the same time, it will require the concerted efforts of stakeholders all along the product chain to minimize avoidable disruptions to the state's established systems.

As this publication goes to press, California already has embarked on a journey to further integrate the front and back ends of products and packaging: in January, 2014, CalRecycle reports to the Legislature on the “75 percent initiative,” gathering many perspectives from across the state. Plastics, packaging, residual organics, contamination, sorting, product stewardship – all the topics in this report and more are under review.

Understanding the role of bioplastics will inform the larger discussion now underway to implement AB 341 and California's interrelated environmental aspirations. Clearly much work is

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ahead to achieve the state's goals, whether it involves minimizing solid waste disposal, reducing greenhouse gasses, eliminating toxic ingredients, or combating ocean pollution – or pursuing all these objectives at once.

Abbreviations, Acronyms, and Glossary of Terms

(Will be published in Final Draft)

Appendix A – Patents filed by Stanford University

1. “Intermittent Nutrient Addition for Synthesis of Polyhydroxyalkanoic Acids Biopolymers by Methane-oxidizing Bacteria.” A method to maximize PHB production in bacteria by providing methane continuously to bacteria while intermittently limiting a specific nutrient, such as nitrogen.
2. “High Solids Fermentation for Synthesis of Polyhydroxyalkanoates From Gas Substrate.” Technology developed by the Stanford team to deliver nutrients in their gas phase for dry fermentation in bacteria cells to produce PHA granules.
3. “Use of hydroxyalkanoic acids as substrates for production of polyhydroxyalkanoates by methane-oxidizing bacteria.” Use of hydroxyalkanoic acids, alone or in addition to methane, as nutrients for production of PHA polymers by methanotrophic bacteria.
4. “High throughput system for isolation, growth, and detection of lipid inclusions in bacteria” Development of a PHB growth system that maximizes the production and analysis of PHB (or any fat molecules) by bacteria.
5. “Method for anaerobic biodegradation of bioplastics.” Development of a way to maintain the stability of PHA plastics during product use, and to enhance degradation for out-of-service breakdown of PHA materials in a landfill environment.
6. “Process for the selection of PHB-producing methanotrophic cultures.” Cycling of nitrogen sources for methanotrophs that produce PHAs in order to selectively enrich microbial cultures and maintain high PHA production rates.
7. “PHBV/Ground Bone Meal and Pumice Powder Engineering Biobased Composite Materials for Construction.” Description for the in-use properties and out-of-use degradation of biocomposite construction materials manufactured from PHAs and filler particles dispersed throughout a matrix.
8. “Intermittent application of reduced nitrogen sources for selection of PHB producing methanotrophs.” Method for the biosynthesis of PHB using methane limitation combined with cycling of nitrogen sources.
9. “Coated biodegradable building article.” Description of biodegradable composite building materials coated with a layer of anaerobically biodegradable composite material (matrix consisting of PHA polymer embedded with small, solid particles).

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